US Army Corps of Engineers
Engineer Institute for Water Resources

# Guidelines for Evaluating Modifications of Existing Dams Related to Hydrologic Deficiencies

ADVANCE COPY



OFFICE OF THE CHIEF OF ENGINEERS



October 1986

IWR Report 86-R-7

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

# REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

| | |
|---|---|
| 1. REPORT NUMBER | IWR REPORT - 86-R-7 |
| 2. GOVT ACCESSION NO. | |
| 3. RECIPIENT'S CATALOG NUMBER | |
| 4. TITLE (and Subtitle) | GUIDELINES FOR EVALUATING MODIFICATIONS OF EXISITING DAMS RELATED TO HYDROLOGIC DEFICIENCIES |
| 5. TYPE OF REPORT & PERIOD COVERED | |
| 6. PERFORMING ORG. REPORT NUMBER | 86-R-7 |
| 7. AUTHOR(s) | Eugene Stakhiv<br>David Moser, Ph.D. |
| 8. CONTRACT OR GRANT NUMBER(s) | |
| 9. PERFORMING ORGANIZATION NAME AND ADDRESS | U.S. Army Corps of Engineers<br>Institute for Water Resources<br>Casey Building, Ft. Belvoir, VA 22060-5586 |
| 10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS | |
| 11. CONTROLLING OFFICE NAME AND ADDRESS | U.S. Army Corps of Engineers<br>Office of the Chief of Engineers<br>20 Mass. Ave., Washington, DC 20314 |
| 12. REPORT DATE | October 1986 |
| 13. NUMBER OF PAGES | 110 |
| 14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) | |
| 15. SECURITY CLASS. (of this report) | Unclassified |
| 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE | |
| 16. DISTRIBUTION STATEMENT (of this Report) | Unlimited |
| 17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report) | |
| 18. SUPPLEMENTARY NOTES | |
| 19. KEY WORDS (Continue on reverse side if necessary and identify by block number) | |
| 20. ABSTRACT (Continue on reverse side if necessary and identify by block number) | |

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

# GUIDELINES

for

# EVALUATING MODIFICATIONS OF EXISTING DAMS RELATED TO HYDROLOGIC DEFICIENCIES

| Accesion For | | |
|---|---|---|
| NTIS CRA&I | ☒ | |
| DTIC TAB | ☐ | |
| Unannounced | ☐ | |
| Justification | | |
| By | | |
| Distribution / | | |
| Availability Codes | | |
| Dist | Avail and / or Special | |
| A-1 | | |

OFFICE OF THE CHIEF OF ENGINEERS

U.S. Army Engineer
Institute for Water Resources

September, 1986

# PREFACE

These guidelines for implementing the Corps' policy on "Evaluating Modification of Existing Dams Related to Hydrologic Deficiencies" are among the first products of the dam safety risk analysis research program. The research program was initiated as a consequence of Secretary Gianelli's request for a "well-ordered spillway design process" for existing dams requiring remedial measures for hydrologic capacity deficiencies. It is expected that the guidelines will be updated and expanded continuously, throughout the course of the research program, as better information and familiarity with risk analysis application is achieved. Since much of the research is underway, the discussion of fundamental evaluation principles (Part II) and guidance for conducting Phase II risk analysis (Part IV) has not been incorporated into this report.

The Institute for Water Resources (IWR) was tasked to develop the necessary evaluation guidelines and analytical techniques needed for dam safety risk analysis. The Hydrologic Engineering Center (HEC) was asked to cooperate with IWR in developing the hydraulic and hydrologic information base for analysis. The guidance to the field operating activities (FOAs) is geared to rapid dissemination of interim guidelines and manuals to assist in preparing dam rehabilitation reports for use in justifying current programmatic budgeting of dam safety new starts. Also, the research program will produce several, more detailed case study analyses and technical reports. Many of the evaluation principles within this manual are derived from the National Research Council's report on "Safety of Dams: Flood and Earthquake Criteria" (1985).

Mr. Donald Duncan, (DAEN-CWR), has been the OCE coordinator of the dam safety risk research program, acting as the designated liaison between the Office of the Assistant Secretary of the Army for Civil Works, the Engineering and Construction Directorate, various OCE divisions, and the Institute for Water Resources. Mr. Vernon Hagen, (DAEN-CWH), who is now retired, initiated the oversight of the hydrology and hydraulics component of the risk analysis research program, especially with respect to the work of the Hydrologic Engineering Center. Mr. Roy Huffman, (DAEN-CWH), currently fulfills that role, jointly sharing the various coordination responsibilities with Mr. Donald Duncan. The research study managers are Mr. Eugene Stakhiv (IWR) and Mr. Arlen Feldman (HEC). This guidelines manual was authored by Eugene Stakhiv and Dr. David Moser (IWR). Messrs. Duncan, Huffman, and Hagen provided detailed review comments on several draft versions, as well as suggestions for restructuring the report. We are grateful to Corps District personnel for their extensive review of the draft guidelines.

TABLE OF CONTENTS

Section I

## INTRODUCTION

The guidelines for evaluating modifications of existing dams related to hydrologic deficiencies currently represent an incomplete and partial fulfillment of an evaluation approach agreed to by the Office of the Secretary of the Army (CW) and the Office of the Chief of Engineers. The broad evaluation philosophy and basis for a two-phased procedure is covered in the DAEN-CW/DAEN-EC policy letter of 8 April 1985 [Appendix B]. The "Guidelines" focus exclusively on procedures which serve to quantify the evaluation principles that underlie the first phase of analysis expressed in the policy letter. A a descriptive convenience, the first phase has been termed hazard assessment in order to separate it from the more formal, analytically oriented risk-analysis phase, which would only be warranted under certain conditions.

It is expected that the Phase I guidelines, contained herein, [Part III], will be reviewed and updated as experience with their application and the results of the research program contribute to the refinement of the evaluation principles and techniques. Phase I guidelines will serve as the nucleus of a manual for dam safety risk analysis which will be continuously updated as new information becomes available.

An overview of the history and evolution of the ideas underlying the Corps' policy is presented in Appendix A of this report. The key point to consider is that the Phase I evaluation philosophy is based on a set of premises which rely on a hypothetical "with" versus "without" dam failure comparison of economic losses and potential loss of life.

Although the "Guidelines" are structured as a series of continuous analytical procedures and display steps, Phase I is a two-part procedure which serves as both a screening device and an evaluation of alternative remedial measures. The idea behind the first part (STEPS 1-11) is to separate the dams requiring remedial measures for hydrologic/hydraulic deficiencies into two categories: (1) those which should be upgraded to fully meet the traditional Probable Maximum Flood (PMF) design criterion, and; (2) those dams which can be considered hydrologically adequate without fully meeting a PMF design. Those dams that are in the second category will require a risk-cost analysis for designs beyond that warranted under Phase I. This risk-cost analysis will be conducted in Phase II. The procedures for Phase II analysis are currently being developed as part of a research program.

The second part of Phase I analysis focuses on the evaluation of alternative remedial measures which can provide the requisite level of dam safety. Both parts rely on the same information base for screening and for choices among alternatives. The basis for choices depends on a comparison of economic losses and/or loss of life "with" and "without" the remedial measures. That is, each proposed alternative remedial measure results in different consequences on the upstream and downstream populations, both in a "non-failure" condition as well as a "failure condition." Furthermore, some remedial measures, such as lowering the spillway crest, may increase the frequency of non-failure flood losses, while others, such as raising the dam crest, may increase the flood losses with dam failure.

The choice of the most risk-cost effective alternative, then, is more than simply selecting the least-cost alternative that will meet the design level warranted by Phase I. The choice requires a judgmental balancing of residual effects, costs, and loss of life developed in detail as part of Phase I analysis. Either economic losses or loss of life or both may serve as a basis for the selection of the most appropriate remedial measure. The procedures provide the requisite analytical steps and display of information needed for this selection.

# SECTION II - TECHNICAL ISSUES

1. Risk and Uncertainty Evaluation Principles
   [To be completed]

2. Hydrologic and Hydraulic Uncertainty
   [To be completed]

3. Economic Foundations of Risk-Cost Analysis
   [To be completed]

4. Loss of Life Estimation Uncertainty
   [To be completed]

5. Impacts (Regional, social and environmental
   [To be completed]

6. Data Requirements
   [To be completed]

# SECTION III - PHASE I GUIDELINES

## Section III

## Example Application of Phase I Analysis of Safety Modifications for Hydrologically Deficient Dams

## List of Tables

List of Figures

## Section III

## Example Application of Phase I Analysis of Safety Modifications for Hydrologically Deficient Dams

### Introduction

This section provides a step by step procedure to conduct Phase I analysis for the evaluation of safety modifications for hydrologically deficient dams based on the policy set forth in the DAEN-CW/DAEN-EC letter of 8 April 1985 (Appendix B). The procedures are primarily intended for the evaluation of structurally sound earthfill dams that may fail if inflow flood events exceed those for which the structure was designed. Because of changes in the rates and volumes of inflow events since the original design and construction, these dams may not safely pass updated estimates of extreme flood events derived by using the current Probable Maximum Precipitation (PMP) estimates from the applicable National Weather Service general or site specific hydrometeorological reports.

Phase I analysis focuses on the assessment of the adverse consequences from reservoir inflow events as a precursor to the formulation of remedial design alternatives. Proposed alternative modifications are designed to reduce the level of the adverse consequences and/or the likelihood of the adverse consequences occurring. Adverse consequences include possible social, economic, and environmental losses that can occur due to abnormally high reservoir levels. Primarily, however, the modifications are considered to reduce the likelihood or consequences of an uncontrolled release of water due to dam or appurtenant structure failure.

The evaluation steps in Phase I serve to establish the <u>base safety condition</u> (BSC) which is the minimum flood event for which the proposed modification should be designed. In determining the BSC, the analyst must evaluate the adverse failure consequences from combinations of alternative modifications and inflow flood events and compare these consequences to those that would have occurred without the failure of the dam from that same set of flood events. The base safety condition flood event is smallest inflow flood where there is no significant increase in adverse consequences from dam failure compared to non-failure adverse consequences. That is, there is no significant increase in <u>loss of life</u> and/or <u>economic loss</u> from dam failure compared to without dam failure. If failure always results in a significant (See Para. 4, Appendix B) increase in losses, regardless of the inflow event, the design flood event chosen for safety modification design purposes should be the PMF. In the event that BSC is determined to be less than the PMF, Phase II analysis, incorporating a probabilistic assessment of failure and non failure losses, may be initiated, <u>if desired</u>, to modify the project for flood events that exceed the BSC.

For hydrologically deficient dams, the primary mode of failure considered here is from overtopping of the dam embankment. It is possible, however, that high flows passing through the spillway may lead to an erosion failure of the spillway. A National Research Council study (1983) showed that of the dams that failed, 30 percent were caused by spillway failure due to erosion during emergency operations. Embankment overtopping causes erosion of the toe and abutments of the dam. If the overtopping flows are long enough in duration, a weakened section is formed in the dam. This weakened section may "burst" with a sudden release of impounded water, or the downcutting may continue forming a breach to the base of the embankment. The downstream peak flows, total volume and, therefore, consequences may differ from the different failure modes: spillway failure or erosion weakened embankment failure.

A failure of the dam will result in at least a short term (3-5 year) loss of some or all of the beneficial outputs produced by the dam/reservoir. The downstream consequences of an embankment failure are likely to be severe. Large areas are likely to be inundated that had never experienced flooding since the settlement of the region. In addition, the extent of the damage within the "normally" flood prone areas will be more severe due to high flow velocities and large sediment load from a dam breach flow. The categories of the economic consequences of flooding considered in STEP 8 are based on, and similar to, those described in the "Principles and Guidelines" (P&G) for the evaluation of the "without condition" flood control project benefits.

The potential for loss of life from dam failure is a primary motivation for considering safety improving investments. Evaluating the population at risk, the threatened population, and loss of life requires the consideration of many factors including the effectiveness of warning and the evacuation of the threatened population. Effective warning and evacuation, where these are practical, may reduce the number of people threatened by the dam failure flood waters as well as non-failure spillway flows.

The succeeding sections provide a step by step procedure for Phase I analysis of dam safety modifications, as well as suggestions for the presentation of results. The outcome of Phase I is the determination of the BSC and the alternative that most effectively achieves the BSC. If it is determined that the BSC is less than the PMF, the choice is either to modify the dam up to the BSC or justify modifying the dam to a higher level up to and including the PMF based on a <u>risk-cost analysis</u> approach. This risk analysis is to be conducted as part of Phase II analysis, the procedures for which are currently being developed as part of the risk research program.

STEP 1 - Describe the Physical Project Characteristics

Purpose

The purpose of STEP 1 is to quantitatively and qualitatively present a summary of the relevant physical characteristics of the project. Much of this information will be used in later steps as the basis for determining the threshold flood and the base safety condition. Most of the information is needed for standard hydrologic analysis of flows relying on computer based models, such as HEC-1.

a. Summarize and display the physical features of the project.

The physical features of the project as constructed should be summarized and displayed in a form similar to Table III-1. Maps of the upstream basin and downstream areas likely to be affected should be displayed, such as that shown in Figure III-1, as well as the general plan, profile, and cross-sections of the embankment and appurtenant structures, such as shown in Figure III-2.

b. Describe the physical features of the project.

The description of the components of the project related to hydrologic deficiency should be provided. These include the composition of the embankment, spillway, and outlet works and an evaluation of their current condition. Any unique circumstances that may impact emergency operations of the spillway or outlet works or that could influence the choice of dam safety modification should be described. These may include any downstream dams whose safety might be adversely affected by emergency operations or failure of the dam being analyzed. A description of the watershed of the project including climate and soil conditions should be provided in figures and/or tables.

c. Describe the operations and use of the project.

The operations and beneficial purposes of the project should be described. For a complete description, Operation, Maintenance and Replacement (OM&R) costs as well as the beneficial products of the project should be included. Yearly expenditure, in constant dollars, and an historical average for OM&R costs and estimated project benefits should be provided for the most recent experience of the project, such as the last 10 years. In addition, the average annual OM&R costs and project benefits, based on frequency analysis, should be evaluated and displayed, such as in Table III-2.

d. Describe the economic development upstream and downstream of the dam.

Emergency operations and safety modification will impact upstream and downstream development. Land use in affected areas should be described including significant industrial, residential and recreational areas. In addition, components of the communications and transportation systems that may be impaired by emergency operation or dam failure, should be identified. These include bridges across the downstream channel and roads adjacent to the channel.

Table III-1

Pertinent Data

| | | |
|---|---|---|
| Drainage Area | sq. mi. | 4,770 |
| Dam (rolled earthfill): | | |
| Crest elevation | ft., m.s.l. | 895 |
| Streambed elevation | ft., m.s.l. | 612 |
| Maximum height above streambed | ft. | 283 |
| Crest length | ft. | 975 |
| Freeboard | ft. | 5 |
| Spillway (detached, broad-crested): | | |
| Crest elevation | ft., m.s.l. | 865 |
| Crest length | ft. | 110 |
| Elevation of maximum water surface | ft., m.s.l. | 890 |
| Discharge at spillway design surcharge | c.f.s. | 41,500 |
| Outlet Works: | | |
| Tunnel (12 ft. diameter) | | |
| Length | ft. | 1,290 |
| Intake invert elevation | ft., m.s.l. | 620 |
| Outlet invert elevation | ft., m.s.l. | 610 |
| Gates (5.5 ft. x 8.5 ft.) | | |
| Service | number | 3 |
| Emergency | number | 3 |
| Discharge at spillway crest elevation | c.f.s. | 7,000 |
| Reservoir: | | |
| Area at: | | |
| Spillway crest | acres | 13,300 |
| Maximum water surface | acres | 16,400 |
| Dam Crest | acres | 17,100 |
| Capacity (gross) at: | | |
| Spillway crest | ac.ft. | 1,043,000 |
| Maximum water surface | ac.ft. | 1,409,000 |
| Dam crest | ac.ft. | 1,499,000 |
| Storage allocation below spillway crest: | | |
| Flood control | ac.ft. | 608,000 |
| Conservation | ac.ft. | 230,000 |
| Recreation | ac.ft. | 5,000 |
| Sedimentation | ac.ft. | 200,000 |
| Standard project flood (design): | | |
| Total volume | ac.ft. | 422,000 |
| Peak flow | c.f.s. | 317,000 |
| Drawdown time (to top of conservation pool) | days | 27 |
| Peak water surface elevation | ft., m.s.l. | 845 |
| Water surface area at peak | acres | 10,900 |
| Inflow design flood (design): | | |
| Total volume | ac.ft. | 893,000 |
| Peak inflow | c.f.s. | 580,000 |
| Peak outflow | c.f.s. | 50,600 |
| Drawdown time (to spillway crest) | days | 12.5 |

FIGURE III-1--MAP OF UPSTREAM AND DOWNSTREAM BASIN

FIGURE III-2—PLAN OF EMBANKMENT AND APPURTENANT STRUCTURES

Table III-2

Project Costs and Benefits
(1975-1985)

Operation and Maintenance Costs: (in constant dollars)

| | |
|---|---|
| 1975 | $1,000,000 |
| 1976 | $1,000,000 |
| 1977 | $1,000,000 |
| 1978 | $1,100,000 |
| 1979 | $1,100,000 |
| 1980 | $1,100,000 |
| 1981 | $1,100,000 |
| 1982 | $1,100,000 |
| 1983 | $1,200,000 |
| 1984 | $1,200,000 |
| 1985 | $1,200,000 |
| 11-year average | $1,100,000 |

Project Benefits: (in constant dollars)

| | Flood Control | Recreation | Total |
|---|---|---|---|
| 1975 | $10,000,000 | $3,500,000 | $13,500,000 |
| 1976 | $12,500,000 | $3,200,000 | $15,700,000 |
| 1977 | $17,000,000 | $2,900,000 | $19,900,000 |
| 1978 | $2,000,000 | $3,700,000 | $5,700,000 |
| 1979 | $20,500,000 | $3,600,000 | $24,100,000 |
| 1980 | $53,000,000 | $3,600,000 | $56,600,000 |
| 1981 | $17,000,000 | $3,400,000 | $20,400,000 |
| 1982 | $7,000,000 | $3,800,000 | $10,800,000 |
| 1983 | $7,500,000 | $4,000,000 | $11,500,000 |
| 1984 | $8,000,000 | $4,100,000 | $12,100,000 |
| 1985 | $9,500,000 | $4,100,000 | $13,600,000 |
| 11-year average | $14,910,000 | $3,630,000 | $18,540,000 |

Average Annual:

O & M..................$1,200,000

Benefits..............$19,500,000

STEP 2 - Determination of the Existing Threshold Flood

Purpose

Based on the existing dam design, there is an inflow flood event that will exceed the design criteria of the dam and threatens dam failure. The purpose of STEP 2 is to determine the existing level of safety of the dam against extreme hydrologic events, (i.e. those events greater than the designed criteria.) This is done by routing flood events, expressed as percentages of the PMF event calculated using the most current appropriate hydrometeorological reports, through the reservoir and identifying the event for which the still water level encroaches on the freeboard necessary to accommodate potential wind and wave conditions and threatens the safety of the structure. It is assumed that the PMF hydrograph has been determined through some acceptable analytical procedure or model using the Probable Maximum Precipitation (PMP) and snowmelt, where appropriate, provided by the National Weather Service. The procedure used should be identified and described. For simplicity, the hydrograph for each percentage of the PMF can be determined by multiplying each of the PMF ordinates by the appropriate percentage.

Key Considerations

1. What should be assumed about the initial level of reservoir water prior to the onset of the threshold flood?

For Phase I analysis, the threshold flood should be composed of two events, an antecedent flood event and a threshold flood event. The initial reservoir water surface elevation should be determined by routing an antecedent event through the reservoir. In the absence of more detailed studies, it can be assumed that the antecedent event begins 5 days prior to the onset of the threshold flood event and should be assumed to be 50 per cent of the succeeding threshold flood. Thus, for a threshold flood of .6 PMF, the antecedent flood should be a .3 PMF event, while for a 1 PMF threshold flood the antecedent flood should be a .5 PMF event. Key Considerations (3), below, discusses the operation of the outlet works and spillway gates, if any, for both the antecedent flood and the threshold flood. This same relationship between the antecedent flood and succeeding flood should be maintained for all floods evaluated. Downstream flow conditions should be consistent with the antecedent conditions used in developing the PMF.

2. What should be assumed about the appropriate level of freeboard?

Freeboard is intended to provide overtopping protection against wave and wind effects on a full reservoir. For Phase I, wave height, wind setup, and wave runup should be computed following current Corps of Engineer guidance, ETL 1110-2-305 for wave height, ETL 1110-2-1614 for wave runup, and equation 3-97 of Shore Protection Manual, Coastal Engineering Research Center, 1977, for wind setup. These calculations should be shown such as in Table III-3. This freeboard computed by the aforementioned methods is the appropriate value for Phase I analysis. According to current engineering guidelines, however, freeboard should always be at least 3 feet.

3. What should be assumed about the operation of spillway gates, if any, and outlet works?

The operation of the outlet works and spillway gates, if any, should follow the regulations set forth in the "Water Control Manual" or historical operating criteria for the project. The outlet works and spillway gates (if gated) should be assumed to be fully operational except if unusual debris accumulation or other difficulties can be anticipated. The gates can be assumed to be less than fully operational but a description of the causes should be discussed, including consideration of any difficulties that project personnel may encounter in traveling to the dam to operate the gates.

The Threshold Flood

Based on the assumptions about antecedent storms, appropriate freeboard, and outlet works and spillway gate operations, the threshold flood, measured as a proportion of the PMF event can be determined. The threshold flood is that flood that results in a peak reservoir water surface elevation equal to the dam crest elevation less the appropriate freeboard. Because of the assumed relationship between the antecedent and design events discussed in Key Consideration (1), above, the threshold flood must be determined by evaluating the water surface elevations for several (at least 4) antecedent/design event combinations, e.g. .125 PMF/.25 PMF, .25 PMF/.50 PMF, .375 PMF/.75 PMF, and .5 PMF/1 PMF. For combinations that would result in flow over the dam embankment, the dam crest should be hypothetically raised in order to route the flood through the spillway and outlet works. Figure III-3 shows the determination of the threshold flood based on seven flood routings.

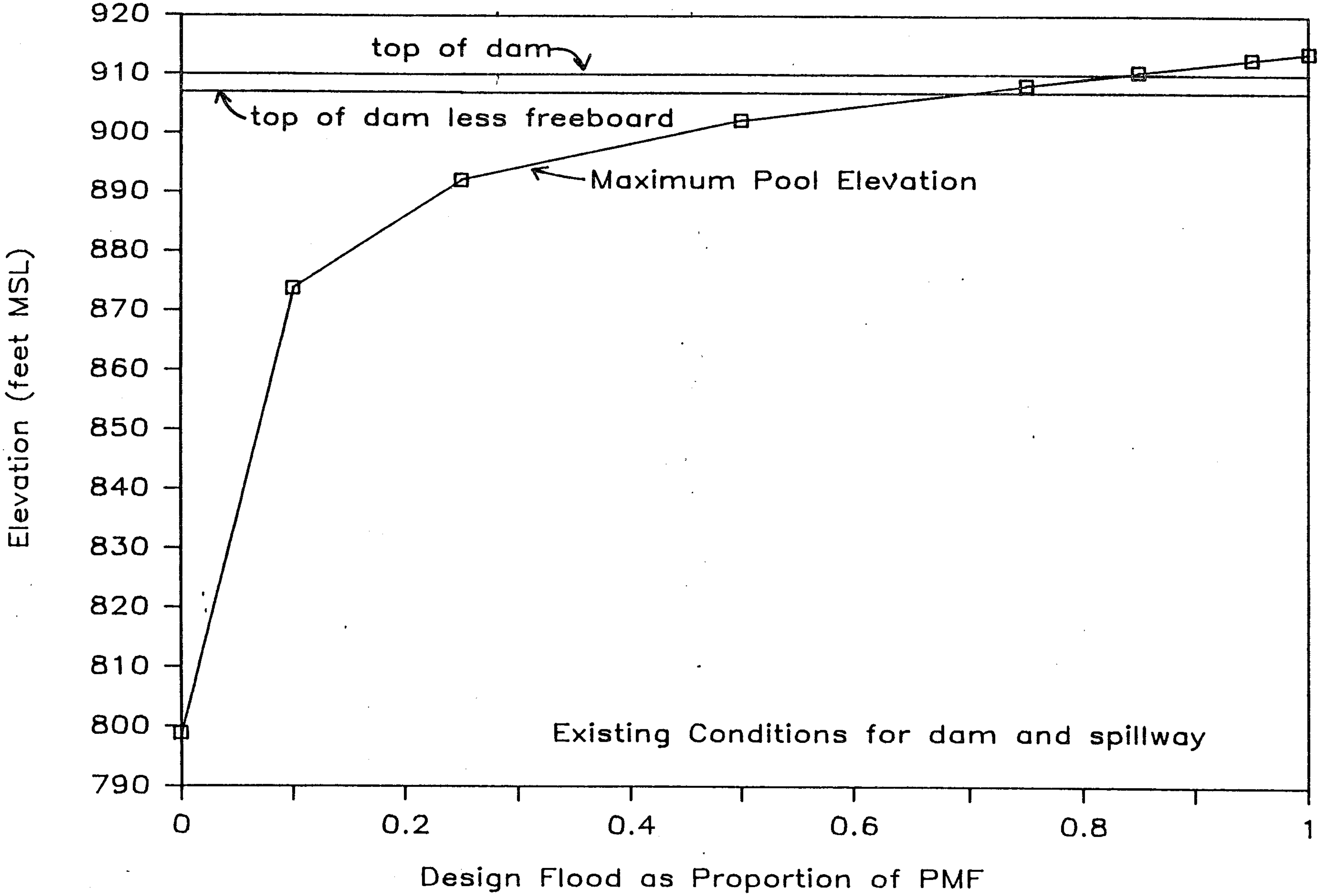
The threshold flood evaluation results should be displayed indicating the peak inflow rate, total volume, its proportion of the PMF flood and the peak outflow rate. Similar results should also be displayed for floods less than the threshold. These will be used to determine the residual (spillway related) flood hazard "with and without" modification.

If the existing condition threshold flood is less than the PMF, further analysis leading to the consideration of dam safety improving alternatives may be warranted. High priority is being given at this time to the evaluation of projects where the current PMF still water elevation will overtop the dam.

TABLE III-3: CALCULATION OF WIND SETUP, WAVE HEIGHT, AND WAVE RUNUP

Figure III—3

Determination of the Threshold Flood



STEP 3 - Determine Total Flows and Downstream Inundation from the Threshold Flood "with and without" Dam Failure and from Lesser Floods

Purpose

The threshold flood, determined in STEP 2, is presumed to result in the formation of a breach in the dam embankment or spillway and provides the basis for considering dam safety modifications. The purpose of STEP 3 is to predict the extent of the increment of downstream inundation from the failure flood and the travel time of the flood wave from the water flowing out of the dam compared to inundation levels from the same inflow flood without dam failure. Outflows include those through the spillway and outlet works as well as the breach. The results of this step will be used to produce inundation maps for the evaluation of potential fatalities and economic losses. This step includes the evaluation of the increased losses from lesser, non-failure floods because some dam safety modifications proposed in STEP 10 may increase the downstream hazard from these lesser floods compared to the existing condition.

Key Considerations

1. Which breach formation and breach flow routing model should be used?

There are three readily available computer models that are useful in predicting dam failure breach flows and downstream inundation. These are: 1.) Simplified Dam-Break (SMPDBK); 2) HEC-1; and 3) National Weather Service Dam-Break (DAMBRK). The most sophisticated and potentially most accurate is DAMBRK. It provides a complete solution to the breach and flow hydraulics. DAMBRK, however, does not have the capability to generate inflow hydrographs, so a watershed model, such as HEC-1, is needed to compute the reservoir and tributary inflow. DAMBRK is the preferred model for dam failure analysis. HEC-1 has somewhat less sophisticated hydraulic calculations than DAMBRK and should not be used for dam failure analysis where significant backwater problems occur. HEC-1 is probably more familiar to most dam designers and dam safety analysts and has the advantage of integrating the hydrologic and hydraulic analyses. SMPDBK is less sophisticated and accurate compared to DAMBRK but may be more accurate for dam failure analysis than HEC-1. The data requirements are less and the ease of use is greater than the other two models. SMPDBK, however, should be used only for a preliminary estimate of the flood wave. Potential users of SMPDBK are cautioned to refer to HEC Research Memo No. 45 for more information about its use.

2. What are the appropriate values of user specified parameters used in modeling the breach formation?

Peak outflows through a breach are very sensitive to several key parameters. These include: time for complete breach development; minimum elevation of breach bottom; breach bottom width; and, breach side slope. Because these parameters may be highly variable for any individual dam, a sensitivity analysis should be conducted to determine the sensitivity of

Table III-4
Typical Initial Dam Breach Parameters

| | |
|---|---|
| Minimum Elevation of Breach Bottom | Stream Bed Elevation |
| Breach Bottom Width | Height of embankment |
| Breach Side Slope | 2 Vertical: 1 Horizontal |
| Breach Development Time | 2 hours |

breach flows to variation in these parameters. This sensitivity analysis will provide a range of most probable breach flows and therefore downstream extent of inundation. Some initial values can be suggested based on the literature on earthfill dam overtopping failure. These are presented in Table III-4. Other values can be used and the most likely values, based on historical data, embankment construction and condition, and professional judgment should be identified. MacDonald and Langridge-Monopolis (1984) have written a useful paper on the subject.

3. Which downstream cross-sectional profiles should be used in the downstream routing?

DAMBRK requires cross-sectional profiles as an input and the accuracy of the other models can be improved by specifying these profiles. Natural river valley constrictions as well as off-channel storage of flood water can modify downstream flows and inundation levels. Therefore, the downstream points for cross sections used in the river routing should be judiciously chosen to reflect these features. Additional cross sections should encompass economic development and population centers, which are of particular interest in the evaluation of the economic and social consequences of dam failure. The HEC program "Geometric Elements from Cross Section Coordinates" (GEDA) can be helpful for developing cross-sections required for DAMBRK.

Threshold Flood Downstream Flows and Inundation

All three models used for dam failure analysis can provide downstream flows and stages from both the threshold flood and smaller events identified in STEP 2. In addition, the models estimate the travel times of the flood wave from the dam to identified points downstream. Therefore, based on the assumptions discussed above, the output of the routing model should be displayed for the floods routed up to and including the threshold flood. This information should include peak flows and water surface elevations for the identified points downstream, as well as, the travel times of the flood wave flows from the dam to inundation of specified elevations or flood zones at the downstream points. For non-failure floods the travel times should be measured from the time of threatening spillway discharge flows until the time the flood water reaches specified stages in each reach downstream. For the threshold flood with failure, the time should be measured from the time the maximum pool elevation is reached until the failure flood reaches specified stages in each reach downstream. Thus, the failure flow time <u>includes</u> the time it takes for the breach to form. Table III-5 provides an example display of the information generated in STEP 3. A stage-hydrograph, displaying the rate of rise at various cross-sections would be equally useful.

TABLE III-5

Summary of Threshold Flood Characteristics

| | Discharge at Dam (cfs) | .5 Elevation (ft. msl.) | .5 Time to Elev.* (hours) | 2 Elevation (ft. msl.) | 2 Time to Elev.* (hours) | 5 Elevation (ft. msl.) | 5 Time to Elev.* (hours) | 10 Elevation (ft. msl.) | 10 Time to Elev.* (hours) |
|---|---|---|---|---|---|---|---|---|---|
| | | Miles Downstream from Dam | | | | | | | |
| | 138000 | 870 | 0 | 867 | 0.5 | 857 | 1.5 | 842 | 5 |
| | 229000 | 875 | 4 | 872 | 4.5 | 862 | 5 | 847 | 8.5 |
| Without Failure | 266000 | 880 | 9 | 877 | 9.5 | 867 | 10 | 852 | 13.5 |
| | 305000 | 885 | 15 | 882 | 15.5 | 872 | 16 | 857 | 19.5 |
| | 324000 | **890 | 24 | **887 | 24.5 | **877 | 25 | **862 | 28.5 |
| | 324000 | 890 | 0 | 887 | 0 | 877 | 0 | 862 | 0 |
| | 405000 | 892 | 0.5 | 889 | 1 | 879 | 1.5 | 864 | 2 |
| With Failure | 450000 | 895 | 1 | 892 | 2 | 881 | 2 | 866 | 4 |
| | 600000 | 899 | 1.5 | 896 | 2.5 | 884 | 3 | 869 | 6 |
| | 779000 | ***907 | 2 | 902 | 3.5 | ***890 | 5 | ***873 | 8 |

NOTE: Discharge at dam without failure shows the progression of discharge over time up to the peak without failure discharge. The discharge at the dam with failure shows the progression of outflows, including the breach flow, up to the peak breach flow at the dam.

* Measured from beginning of spillway flow without failure and from the beginning of breach with failure

** Threshold flood maximum elevation <u>without</u> failure.

***Threshold flood maximum elevation <u>with</u> failure.

STEP 4 - Compute the Hypothetical Maximum Dam Failure Flows and Downstream Inundation

Purpose

The purpose of STEP 4 is to determine the maximum lateral boundaries for the collection of data on economic and life losses for the succeeding steps. The combination of raising the dam crest and a PMF event results in determining the hypothetical maximum lateral extent and depth of flooding from dam failure. All lesser failure and non-failure floods will inundate a subset of this area. Therefore, the collection of data on damageable property and population downstream from a dam can be accomplished with a single effort. The assumptions for the failure routing for this hypothetical event should be consistent with those used in STEP 3.

The collection of data cannot be limited merely to the zone or increment between the flood stage due to the threshold failure flood and the maximum PMF failure flood for several reasons. Foremost is the desirability of data consistency and analytical uniformity. Much of the analysis will depend on excellent secondary data sources which are often more current than the existing inventories of structures which have been updated only to reflect inflation. This means that the updated original flood damages prevented by the project may differ from the computation based on secondary, but more current sources. For the sake of uniformity of approach and consistency of results, the entire lateral zone of inundation needs to be reexamined. The second reason for collecting data for the entire inundated area is that certain modifications can impose residual damages, upstream and downstream, for flood events less than the threshold flood. Thus, the increment in damages below the threshold flood may become a significant consideration in selecting the most economical alternative.

STEP 5 - Prepare Inundation Maps and Collect Data on Damageable Property and Populations for the Hypothetical Maximum Flooding Determined in STEP 4

Purpose

STEP 4 determined the hypothetical maximum dam failure condition for the purposes of data collection. STEP 5 requires the collection of data for use in estimating economic flood losses and life losses in the succeeding steps. All other failure and non-failure flood events will affect only a portion of this property and population.

Key Considerations

Is a complete survey of potential losses in the inundated areas required?

One difficulty with estimating flood damage from a dam failure flood or even a spillway flood is that large areas may experience flooding for the first time. Little information about the land use and economic activities may be known for these areas. Because of the uncertainties about the extent of flooding and the impact of failure flow velocities and sediment load on structures, secondary data should be used as much as possible. This is particularly true in urban areas where development is extensive but where a wealth of data may currently be available. Secondary data sources include National Flood Insurance claims data, Census of Population and Census of Business, other published reports, and local property tax assessment records. Some field verification of estimates based on secondary data is required and the estimate of both dam failure and non-failure flood losses should be made employing past experience, local knowledge, and professional judgment.

It is recommended that the inundated area be divided into flood depth zones. The average depth of flooding in any zone can then be used in estimating damage from existing depth-percent damage relationships. In addition, the inundated area should be identified by land use types such as residential commercial, industrial, agriculture, etc. These land use types can be further subclassified based on other factors such as average home value. Therefore, average estimation of structure and contents value can be applied to the various land use classifications. It is not practical to collect damage data on a structure-by-structure basis. Therefore, methods that rely on statistical sampling and analysis should be considered.

STEP 6 - Prepare Inundation Maps for Threshold Flood.

Purpose

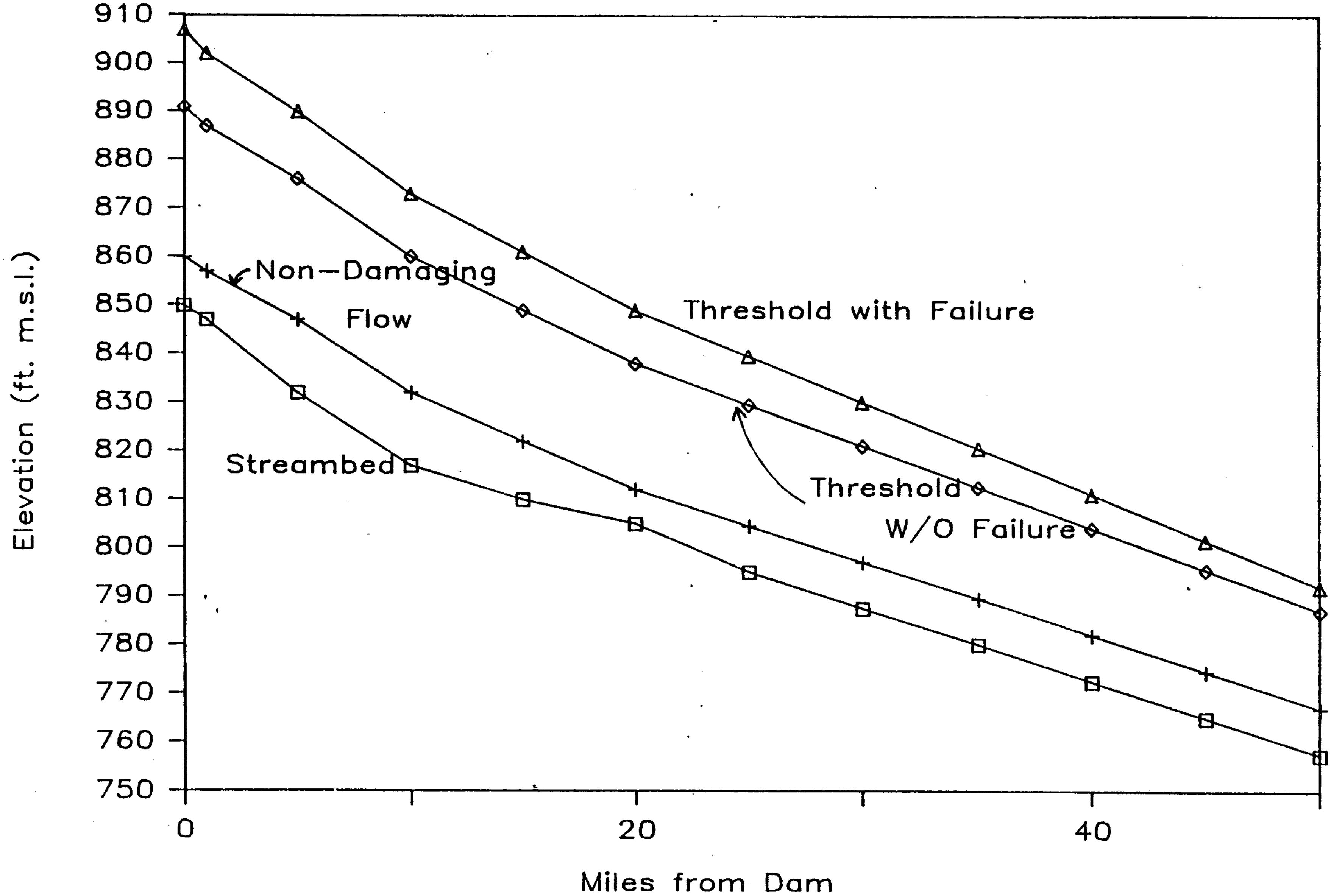
The output of STEP 3 includes river stages at various points downstream from the dam resulting from the threshold flood induced dam breach as well as lesser flood events safely passed by the dam. The purpose of STEP 6 is to identify downstream areas inundated from the flood events. This step is a follow-up to STEP 5 which delineates the lateral boundaries of the "hypothetical maximum" dam failure flood event. Of primary interest is the difference in the extent of the affected areas at the threshold flood with and without dam failure. This information will be used to determine economic flood losses and the population threatened by failure and nonfailure floods. Maps ought to show the lateral extent of flooded areas, including a characterization (by zones or cells) of the population, cross-sectional profiles of stream gradient, flood stages and significant economic, cultural, and ecological features. Figures III-4, -5, and -6 show an example for presenting this information. Because the population immediately downstream from the dam (less than 2 hours travel time) is likely to have the least warning, the maps of the inundated areas and population at risk for the first few miles downstream should be in a larger scale (for example 1:24,000 USGS quad sheet) showing the affected areas in greater detail, if possible. Smaller scale maps (1:250,000) may be used for report summary purposes, to show the characteristics of the downstream areas beyond the 2 hours travel time limit. Maps prepared for emergency warning and evacuation planning at the larger scale (1:24,000) and that are used for detailed stage-damage analysis ought to be included in an appendix to the report.

FIGURE III-4—DETAILED MAP OF INUNDATION AREAS IMMEDIATELY DOWNSTREAM OF DAM (1:24,000)

FIGURE III-5—MAP OF INUNDATION AREAS (1:250,000)

# Figure III—6

Stream Profiles



## STEP 7 - Determine Population at Risk from the Threshold Flood and Lesser Events

### Purpose

A major reason for improving dam safety is to avoid the loss of life that would likely occur from a dam failure. The purpose of STEP 7 is to determine the number of persons that might be exposed to flood waters. Because of the current state of the art in predicting flood caused fatalities, the population at risk (PAR) will be defined as all those persons that would be exposed to flood waters <u>if they took no measures to evacuate</u>. The PAR will be used in STEP 10 to estimate the <u>threatened population</u> (TP) and <u>loss of life</u> (LOL).

### Key Considerations

1. Is the PAR the same for all flood events?

The PAR is generally different depending on the extent of inundation. Thus, since larger floods inundate larger areas, more people may be exposed to flood waters.

2. Is the PAR the same throughout the day and time of year?

The downstream PAR can vary depending on the time of day and season of the year. For instance, a projected inundation area may contain large employment centers that are almost unoccupied during night time hours. Therefore, a night time failure flood wave would expose fewer people to flood waters than a daytime failure flood wave. Conversely for residential areas, night time failures are likely to expose more people to flood waters than daytime failure. Another reason for variation in the PAR is that the downstream area may contain recreation sites that may have large transient populations but only during specific seasons of the year. These different PAR's should be estimated separately to allow adjustment in likely fatalities.

3. Wouldn't warning and evacuation reduce the PAR?

Warning and evacuation will be considered in estimating the <u>threatened population</u>. The threatened population will be defined as those persons likely to be exposed to flood waters assuming that warnings have been issued in a manner that could be expected under current conditions. In the future. as refinements in the models for estimating the PAR become available, they will be incorporated into an empirical loss of life (LOL) model.

### Determining the PAR

The PAR is defined as all those persons that would be exposed to flood waters if they took no measures to evacuate. The PAR, TP, and LOL will be adjusted in STEP 10 to determine the <u>probable PAR</u> , <u>probable TP</u>, and <u>probable LOL</u> by considering the season of year and time of day that a dam failure may occur. The season or period of the year selected should be consistent with assumptions made in computing the PMF (i.e. rainfall on snowmelt, tropical storm, ect.) These probable values should not be confused with expected PAR, expected TP, or expected LOL which is the expected value of PAR, TP, and LOL, respectively, based on the probability of dam failure. These expected values will be explored in Phase II as part of a risk-cost analysis, if needed. Based on the inundation maps from the existing condition threshold flood and specified lesser floods, areas of inundation were identified in STEP 6. Using secondary data as much as possible, the permanent and transient population in the threatened areas should be estimated. The transient population should be identified in terms of the time of day and/or season these individuals are likely to be in the threatened area. Special care must be taken in estimating the population in vehicles traveling through the area. The PAR's should be identified by flood depth zone in each reach since the time to inundation for each zone will differ. Each of the PAR's should also be identified in terms of the minimum potential warning time. This time should be measured for the threshold flood, as well as all other failure floods, as the time from maximum pool elevation until the flood wave arrives at each PAR. For lesser non-failure floods, this time should be measured from the time of spillway discharge threatening flows until the flood water arrives at each PAR.

The display of the PAR should be in a form similar to that in Table III-6. Data for each reach downstream of the dam should be reflected in a separate table. (The 4 foot flood zone increments shown in Table III-6 reflect the use of computer database analysis and interpolation across contours.) A second table such as Table III-7 provides a summary of the maximum daily and seasonal PAR in each reach. The values in Table III-7 are referred to as conditional since each PAR shown is conditional on the flood event occurring during the indicated time of day/season of the year combination. The following definitions should be used in measuring the PAR categories.

a. Permanent Population - total number of individuals who live in the threatened areas year round.

b. Seasonal Transients - the total number of individuals who are only present in the threatened area during particular seasons of the year. These are likely to be recreational visitors and seasonal workers. This category should also include the season component of persons traversing the threatened area in vehicles.

c. Daily Transients - the total number of individuals who are present in the threatened area only during certain time of the day. They do not reside in the threatened area but may work or attend school in the area or regularly travel through the threatened area.

Table III-6

Population at Risk in Specified Flood Zones from Flood Event
by Season of the Year and Time of Day

(a)
Reach 1

| Flood Event | Flood Zone (interval in feet) | Permanent Population | | Seasonal Transient Population | | | | | | | | Daily Transient Population | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | W | | Sp | | S | | F | | | |
| | | D | N | D | N | D | N | D | N | D | N | D | N |
| .10 PMF (peak stage = 4 ft) | 0 - 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | Total | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| .25 PMF (peak stage = 8 ft) | 0 - 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 4 - 8 | 70 | 100 | 0 | 0 | 2 | 0 | 20 | 5 | 2 | 0 | 0 | 0 |
| | Total | 70 | 100 | 0 | 0 | 2 | 0 | 20 | 5 | 2 | 0 | 0 | 0 |
| .50 PMF (peak stage = 12 ft) | 0 - 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 4 - 8 | 70 | 100 | 0 | 0 | 2 | 0 | 20 | 5 | 2 | 0 | 0 | 0 |
| | 8 - 12 | 60 | 95 | 0 | 0 | 7 | 2 | 50 | 15 | 7 | 2 | 100 | 20 |
| | Total | 130 | 195 | 0 | 0 | 9 | 2 | 70 | 20 | 9 | 2 | 100 | 20 |
| .75 PMF (peak stage = 16 ft) | 0 - 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 4 - 8 | 70 | 100 | 0 | 0 | 2 | 0 | 20 | 5 | 2 | 0 | 0 | 0 |
| | 8 - 12 | 60 | 95 | 0 | 0 | 7 | 2 | 50 | 15 | 7 | 2 | 100 | 20 |
| | 12 - 16 | 300 | 400 | 0 | 0 | 4 | 0 | 40 | 5 | 4 | 0 | 50 | 10 |
| | 16 - 20 | 500 | 800 | 0 | 0 | 5 | 1 | 350 | 65 | 10 | 4 | 40 | 10 |
| | Total | 930 | 1395 | 0 | 0 | 18 | 3 | 460 | 90 | 23 | 6 | 190 | 40 |
| .75 PMF With Failure (peak stage = 36 ft) | 0 - 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 4 - 8 | 70 | 100 | 0 | 0 | 2 | 0 | 20 | 5 | 2 | 0 | 0 | 0 |
| | 8 - 12 | 60 | 95 | 0 | 0 | 7 | 2 | 50 | 15 | 7 | 2 | 100 | 20 |
| | 12 - 16 | 300 | 400 | 0 | 0 | 4 | 0 | 40 | 5 | 4 | 0 | 50 | 10 |
| | 16 - 20 | 500 | 800 | 0 | 0 | 5 | 1 | 350 | 65 | 10 | 4 | 40 | 10 |
| | 20 - 24 | 200 | 380 | 0 | 0 | 2 | 0 | 20 | 5 | 2 | 0 | 0 | 0 |
| | 24 - 28 | 400 | 975 | 0 | 0 | 3 | 2 | 15 | 2 | 3 | 0 | 20 | 5 |
| | 28 - 32 | 100 | 100 | 0 | 0 | 4 | 0 | 40 | 5 | 4 | 1 | 30 | 15 |
| | 32 - 36 | 500 | 100 | 0 | 0 | 5 | 1 | 0 | 0 | 0 | 0 | 60 | 10 |
| | Total | 2130 | 2950 | 0 | 0 | 32 | 6 | 535 | 102 | 32 | 7 | 300 | 70 |

* 0 - 4 flood zone begins at bank full stage
D = DAYTIME (between 0800 and 1600)
N = NIGHTTIME (between 1600 and 0800)
W = WINTER  Sp = SPRING  S = SUMMER  F = FALL

Table III-6 (cont.)

Reach 2
(b)

| Flood Event | Flood Zone* (interval in feet) | Permanent Population | | Seasonal Transient Population | | | | | | | | Daily Transient Population | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | W | | Sp | | S | | F | | | |
| | | D | N | D | N | D | N | D | N | D | N | D | N |
| .10 PMF | 0 - 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| (peak stage = 2 ft) | Total | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| .25 PMF | 0 - 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 4 - 8 | 40 | 75 | 15 | 2 | 50 | 40 | 125 | 100 | 40 | 30 | 2 | 0 |
| (peak stage = 6 ft) | Total | 40 | 75 | 15 | 2 | 50 | 40 | 125 | 100 | 40 | 30 | 2 | 0 |
| .50 PMF | 0 - 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 4 - 8 | 40 | 75 | 15 | 2 | 50 | 40 | 125 | 100 | 40 | 30 | 2 | 0 |
| (peak | 8 - 12 | 30 | 50 | 5 | 0 | 80 | 30 | 100 | 80 | 60 | 30 | 7 | 10 |
| stage = 10 ft) | Total | 70 | 125 | 20 | 2 | 130 | 70 | 225 | 180 | 100 | 60 | 9 | 10 |
| .75 PMF | 0 - 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | 4 - 8 | 40 | 75 | 15 | 2 | 50 | 40 | 125 | 100 | 40 | 30 | 2 | 0 |
| (peak | 8 - 12 | 30 | 50 | 5 | 0 | 80 | 30 | 100 | 80 | 60 | 30 | 7 | 10 |
| stage = | 12 - 16 | 200 | 350 | 40 | 30 | 15 | 5 | 15 | 10 | 10 | 5 | 40 | 5 |
| 18 ft) | 16 - 20 | 125 | 200 | 10 | 3 | 15 | 5 | 20 | 10 | 15 | 5 | 5 | 5 |
| | Total | 395 | 675 | 70 | 35 | 160 | 80 | 260 | 200 | 125 | 70 | 54 | 20 |
| .75 PMF | 0 - 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| With | 4 - 8 | 40 | 75 | 15 | 2 | 50 | 40 | 125 | 100 | 40 | 30 | 2 | 0 |
| Failure | 8 - 12 | 30 | 50 | 5 | 0 | 80 | 30 | 100 | 80 | 60 | 30 | 7 | 10 |
| | 12 - 16 | 200 | 350 | 40 | 30 | 15 | 5 | 15 | 10 | 10 | 5 | 40 | 5 |
| (peak | 16 - 20 | 125 | 200 | 10 | 3 | 15 | 5 | 20 | 10 | 15 | 5 | 5 | 5 |
| stage = | 20 - 24 | 100 | 100 | 0 | 0 | 0 | 0 | 5 | 1 | 0 | 0 | 0 | 0 |
| 32 ft) | 24 - 28 | 200 | 40 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 10 | 30 |
| | 28 - 32 | 400 | 500 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 5 | 10 |
| | Total | 1095 | 1315 | 70 | 35 | 160 | 80 | 265 | 201 | 125 | 70 | 69 | 60 |

* 0 - 4 flood zone begins at bank full stage
D = DAYTIME (between 0800 and 1600)
N = NIGHTTIME (between 1600 and 0800)
W = WINTER  Sp = SPRING  S = SUMMER  F = FALL

Table III-7

CONDITIONAL PAR IN EACH REACH

| Reach | | PAR in Each Season/Time of the Day Combination D/W | N/W | D/Sp | N/Sp | D/S | N/S | D/F | N/F |
|---|---|---|---|---|---|---|---|---|---|
| 1 | .10 PMF | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | .25 PMF | 122 | 175 | 124 | 175 | 180 | 190 | 124 | 175 |
| | .50 PMF | 282 | 290 | 291 | 292 | 390 | 320 | 291 | 292 |
| | .75 PMF | 1120 | 1435 | 1138 | 1438 | 1580 | 1525 | 1143 | 1441 |
| | .75 PMF* | 2430 | 3020 | 2462 | 3026 | 2965 | 3122 | 2462 | 3027 |
| 2 | .10 PMF | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | .25 PMF | 63 | 80 | 138 | 125 | 273 | 260 | 128 | 115 |
| | .50 PMF | 105 | 142 | 255 | 215 | 410 | 400 | 225 | 205 |
| | .75 PMF | 525 | 735 | 655 | 785 | 815 | 980 | 620 | 775 |
| | .75 PMF* | 1240 | 1415 | 1370 | 1465 | 1535 | 1661 | 1335 | 1455 |
| 3 | .10 PMF | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | .25 PMF | 902 | 780 | 915 | 782 | 1400 | 1080 | 1000 | 830 |
| | .50 PMF | 1002 | 810 | 1020 | 813 | 1550 | 1130 | 1100 | 860 |
| | .75 PMF | 1134 | 936 | 1095 | 995 | 1720 | 1250 | 1300 | 1892 |
| | .75 PMF* | 1602 | 1600 | 1620 | 1603 | 2150 | 1920 | 1700 | 1650 |
| 4 | .10 PMF | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | .25 PMF | 55 | 82 | 55 | 82 | 55 | 82 | 55 | 82 |
| | .50 PMF | 158 | 274 | 158 | 274 | 158 | 274 | 158 | 274 |
| | .75 PMF | 238 | 402 | 300 | 462 | 235 | 401 | 225 | 420 |
| | .75 PMF* | 520 | 890 | 650 | 920 | 750 | 970 | 500 | 880 |

* Threshold Flood with Failure

D/W = daytime and winter
N/W = nighttime and winter
D/Sp = daytime and spring
N/Sp = nighttime and spring
D/S = daytime and summer
N/S = nighttime and summer
D/F = daytime and fall
N/F = nighttime and fall

## STEP 8 - Determine Economic Losses from Threshold Flood and Specified Lesser Floods

### Purpose

One of the considerations in evaluating dam safety improving investments is the increment in economic loss with dam failure compared to the economic loss without failure. If with failure related economic losses are significantly greater than losses from the same inflow flood without failure, an investment to improve the safety of the dam may be warranted. In the evaluation of flood damages from failure flows, consideration may be given to velocity effects that may result in greater flood damage from a given flood depth than normally estimated by standard depth-damage functions. Adjustments to damages for flood flow velocity should be documented and explained.

### Key Considerations

1. What items should be included as downstream economic losses?

Although "Principles and Guidelines" (P&G) does not provide procedures for dam safety studies, it does contain applicable economic damage computational guidelines (Flood Control, Section III for agriculture and Section IV for urban) for identifying the acceptable categories of economic losses from dam failure to include:

a. Residential structure and content damage
b. Commercial and industrial structure and content damage
c. Agricultural losses
d. Net income losses to business and individuals
e. Flood damage to utility, transportation and communication systems
f. Flood damage to public structures and contents
g. Other flood damage such as vehicles and landscaping improvements
h. Flood emergency costs
i. Project benefits lost with failure

2. What items should be included as upstream economic losses?

The upstream economic losses are those that may be associated with abnormally high reservoir water levels as well as income and/or wealth losses to activities made possible or enhanced by the reservoir. Consideration of these economic values may be important in evaluating alternatives that raise the dam or in the analysis of intentionally breaching the dam. These can include:

a. Income losses to reservoir related recreation business
b. Losses in value to property adjacent to the reservoir
c. Damage to property due to abnormal reservoir levels
d. Relocation costs

3. How can cultural and environmental assets affected by abnormally high reservoir levels and downstream flooding be quantified?

High reservoir levels and downstream flooding from rare floods may permanently damage or destroy important environmental and cultural resources. It is difficult to attach a monetary value to these losses. One approach could be to use the contingent value method to determine the value. In most cases, however, these especially important flood losses can only be identified in relation to the flood events. For some environmental resources, the duration of inundation may determine if the damage is temporary or permanent. These non-monetary damages may be used to influence the choice of the remedial measure. For instance, raising a dam may threaten an important rare stand of woods or wildlife refuge through more frequent and longer duration backwater flooding.

4. How can non-fatal human health effects, such as psychological impairment and physical injury due to flooding, be quantified?

In addition to the expenses of treating flood induced health problems, there have been several recent attempts to monetize the human health impairment, i.e. "trauma damages," caused by flooding. One example is documented in "Estimate of Flood-Related Human Costs in the 1983 Flood at Jackson, Mississippi," IWR Special Study for the Mobile District, U.S. Army Engineer Institute for Water Resources, 84-RS-2, 1984.

Display of Results from STEP 8

The economic losses from the existing condition threshold flood as well as the specified lesser floods should be displayed in current year terms. For example, Table III-8(a) shows an example for presenting the estimated downstream economic losses from a threshold of .75 PMF as well as from 0.1 PMF, .25 PMF and .5 PMF floods, if they occurred during 1986. Table III-8(b) shows an example for presenting the estimated upstream economic losses from the same series of inflow events in the same year.

Table III-8(a)

Downstream
Economic Losses from the
Threshold Flood and Selected Lesser Events

| River Reach | Flood Event | Economic Loss Category* A | B | C | D | E | F | G | Subtotal by Event |
|---|---|---|---|---|---|---|---|---|---|
| 1 | .10 PMF | | | | | | | | |
| | .25 PMF | | | | | | | | |
| | .50 PMF | | | | | | | | |
| | .75 PMF** | | | | | | | | |
| | .75 PMF*** | | | | | | | | |
| 2 | .10 PMF | | | | | | | | |
| | .25 PMF | | | | | | | | |
| | .50 PMF | | | | | | | | |
| | .75 PMF** | | | | | | | | |
| | .75 PMF*** | | | | | | | | |
| 3 | .10 PMF | | | | | | | | |
| | .25 PMF | | | | | | | | |
| | .50 PMF | | | | | | | | |
| | .75 PMF** | | | | | | | | |
| | .75 PMF*** | | | | | | | | |

*Categories

A. Residential
B. Commercial/Industrial
C. Income
D. Utility, Transportation, and Communication
E. Public Property
F. Other Property Losses
G. Flood Emergency Costs

** Threshold Flood Event without Dam Failure
*** Threshold Flood Event with Dam Failure

Table III-8(b)

Upstream
Economic Losses from the
Threshold Flood and Selected Lesser Events

| Flood Event | Economic Loss Category* A | B | C | D | E | F | G | Total by Event |
|---|---|---|---|---|---|---|---|---|
| .10 PMF | | | | | | | | |
| .25 PMF | | | | | | | | |
| .50 PMF | | | | | | | | |
| .75 PMF** | | | | | | | | |
| .75 PMF*** | | | | | | | | |

*Categories

A. Residential
B. Commercial/Industrial
C. Income
D. Utility, Transportation, and Communication
E. Public Property
F. Other Property Losses
G. Flood Emergency Costs

** Threshold Flood Event without Dam Failure
*** Threshold Flood Event with Dam Failure

STEP 9 - Determination of Dam Failure Warning Time

Purpose

The time available to warn the PAR's in each reach prior to the arrival of a flood wave is crucial to reducing the LOL from a rare event flood. The purpose of STEP 9 is to describe the warning process and to show the appropriate calculation of warning time for Phase I analysis. The estimated warning time will be used in estimating the baseline threatened population, TP, in STEP 10.

Key Considerations

1. When is a warning likely to be issued?

The time at which a warning is issued depends on site and event characteristics. In general, a staged series of warnings, which are part of an overall plan for emergency actions and evacuation, will be issued when a spillway flood is in progress and it is thought that a dangerous situation is probable based on weather and river flow forecasts. The threatened population can be thought of as the those individuals remaining in flooded areas after warning and evacuation has been initiated and who are actually exposed to the flood waters.

2. How is warning time measured?

The warning time is measured as the difference in time from when a public warning is initially disseminated about a potential dam failure condition (overtopping or dam breach) until the flood wave reaches each PAR. Thus, warning time is likely to be different for different PAR's. This definition of warning time follows that developed by the Hydrology Subcommittee of the Interagency Advisory Committee on Water Data and reported in "Guidelines on Community Local Flood Warning and Response Systems" (August, 1985). The Interagency Committee defines actual flood warning time as the time from when a warning is issued to the public until the first occurrence of flooding.

The Warning Process

It is assumed that project personnel are at the dam, monitoring the weather and river stages as well as runoff forecasts, prior to the time that water encroaches on the freeboard and are able to implement the procedures described in the "Flood Emergency Procedures Manual" for the project. Therefore, project personnel should be in a position to detect the need to publicly warn the downstream population. The warning dissemination process takes time. Under the extreme conditions occurring which lead to potential dam overtopping, however, there is some lead time given that the spillway flood itself comprises a large, threatening event. Thus, public awareness has been heightened to this factor. Any warning to PAR's to evacuate must first be issued to the local authorities who then must disseminate the warning to the public. Any interruption or delay in this process reduces the amount of warning time and increases the threatened population.

The effectiveness of warning can be reduced by several factors, among them:

a. The preceding storms, urban flooding, and existing high water conditions may disrupt utility, communications and transportation system in the area. The project personnel and local authorities may have difficulty in traveling to the dam site, as well as, issuing and disseminating the warning. These same conditions may make it difficult for some PAR's to evacuate even if they receive a warning.

b. Some of the PAR may have special difficulties in evacuating such as the elderly, the hospitalized or the institutionalized. Telephone directories may be out of date and the inaccessible populace may not be adequately warned. Large numbers of these special populations in the PAR may result in a higher LOL than the baseline. These groups with special evacuation difficulties should be identified to the extent possible as part of any emergency warning evacuation plan.

c. The urgency of the issued warning.

<u>The Warning Time for Each PAR</u>

There is a PAR in each reach and each flood depth zone downstream of the dam for each flood event. Warning time for each PAR begins when the local authorities disseminate an evacuation warning. The time elapsed from public warning issuance until the flood wave arrives at flood depth zone of a particular PAR is the warning and evacuation time for that PAR. Table III-9 shows a time line from the time that the warning is issued to the local authorities until the peak discharge from the dam is reached. Table III-10 shows the flood wave travel times from the dam to the midpoints of the downstream reaches for flood depth zones in each reach.

Therefore, based on Table III-9 and III-10, the minimum available warning times for each PAR can be estimated, for this example, as the flood wave travel times for each flood zone/river reach combination plus the time between warning issuance and dam overtopping.

If there is no rational basis for assuming that adequate warning may be given <u>before</u> overtopping or breach formation occurs, it may be reasonable to assume that the onset of a warning plan or official notification begins when the <u>maximum design pool elevation is reached</u>. Table III-9 shows this initiation of notification beginning 1 hour before actual overtopping or breaching occurs. In this example, warning time begins 1/2 hour before the beginning of the failure flood wave travel time.

Table III-9

Time Line of Warning Process

| Time (hours) | Warning Process Event |
|---|---|
| -.5 | Warning issued to local authorities to evacuate threatened downstream areas. |
| 0 | Public warnings issued to all threatened downstream areas. |
| .5 | Overtopping of dam begins. |
| 1.0 | Maximum breach and outflow occurs. |

Table III-10

Flood Wave Travel Times by Reach and Flood Zone

| | | Flood Wave Travel Time* (hours) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Distance from Population Center of Reach to Dam | Flood Depth Zone in Feet | | | | | | | |
| River Reach | (miles) | 0-4 | 4-8 | 8-12 | 12-16 | 16-20 | 20-24 | 24-28 | 28-32 |
| 1 | 0.5 | ** | ** | ** | 0.5 | 0.5 | 0.5 | 0.5 | 0.6 |
| 2 | 2.0 | ** | ** | 0.7 | 0.8 | 0.8 | 0.8 | 0.9 | N/A |
| 3 | 11.5 | ** | 0.8 | 0.9 | 1.0 | 1.2 | 1.5 | N/A | N/A |
| 4 | 22.5 | ** | 1.5 | 2.0 | 3.0 | 3.5 | N/A | N/A | N/A |

* Time measured from time of overtopping until flood wave reaches indicated flood zone

** Zone inundated by spillway flood prior to overtopping

N/A = Flood Zone not inundated by failure flood

NOTE: Minimum potential warning time for the PAR in each flood zone is flood wave travel time to each zone in each reach <u>plus the time between public issuance of warning and dam overtopping</u>. From Table III-9, time between full issuance of public warning and overtopping in this example is .5 hours.

STEP 10 - Estimate the Baseline Probable PAR, Probable TP, and Probable LOL from the Threshold Flood and Specified Lesser Floods

Purpose

Phase I dam safety analysis requires the estimation of the probable PAR, probable TP, and probable LOL from the existing condition threshold flood as well as lesser floods. In STEP 10, the probable PAR, probable TP, and probable LOL are estimated based on the PAR estimates determined in STEP 8 and the warning time in STEP 9. A significant increment in the probable LOL from the failure of the dam compared to the LOL from the same inflow flood without dam failure provides the basis for considering dam safety improving modifications to hydrologically deficient dams.

At this time there is no generally accepted method of estimating the effectiveness of warning to calculate the probable TP and probable LOL from flooding events. Research indicates that the warning time for each PAR is a key factor in estimating the LOL from dam failure flooding. Ongoing dam safety research should provide an acceptable methodology for estimating TP and LOL. Until this research is completed, the probable PAR is the most defensible measure for establishing the BSC, complementary to incremental economic losses. Nevertheless, estimates of the probable TP and probable LOL must be made, if only on the basis of professional judgement and described qualitatively. Basic considerations in describing the TP and LOL include:

1) the variation in the PAR based on time of day and season of the year,
2) the warning time for the PAR's,
3) the rate of rise and flow velocity of flood water at downstream inundation areas,
4) the flooding conditions in the threatened areas prior to dam failure that may make warning and evacuation difficult,
5) the orientation of evacuation routes relative to the flood wave, and
6) other considerations such as discussed in STEP 9.

Estimating the Probable PAR and Probable TP

The estimates of the TP for the threshold flood and lesser floods in Phase I analysis requires the evaluation of the effectiveness of warning and evacuation reducing the number of people exposed to flood waters compared to the PAR. Current research in dam safety is aimed toward investigating warning and evacuation as well as the applicability of evacuation simulation models for estimating the threatened population.

The values for PAR shown in Table III-7 assume that the flood event occurs during the year but they are still conditional on the season and time of day. The seasonality used should be consistent with the assumptions used in determining the PMF. The maximum and minimum values of the PAR for each flood event up to and including the threshold flood should be displayed. If the flood event used in the analysis is not season specific, the annual range of PAR should be provided. The range of probable PAR is determined from the season/time of day combinations of the conditional PAR estimates in Table III-7. The results of the range determination are presented in Table III-11 for probable PAR. It is assumed in the example that the threshold flood is produced by rainfall on snow melt only. All the lesser events can occur from a variety of rainfall events, so they are equally likely throughout the year.

Note that since there is generally a one-to-one relationship between discharge at the dam and downstream PAR, the information on PAR can be organized into a discharge-PAR function for the full range of discharges with and without dam failure. This can facilitate the determination of effects on downstream PAR from the alternative safety modifications, as each modification will alter the with and without failure discharges from the range of flood events considered.

From Table III-11, the probable PAR from dam failure at the threshold flood is over 50 per cent greater than the probable PAR if the dam had not failed from this flood.

Table III-11

RANGE OF PROBABLE PAR

| Flood Event | Range of PAR in Reach 1 Min. | 1 Max. | 2 Min. | 2 Max. | 3 Min. | 3 Max. | 4 Min. | 4 Max. | Range of Par by Event Min. | Max. |
|---|---|---|---|---|---|---|---|---|---|---|
| .10 PMF | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| .25 PMF | 122 | 190 | 63 | 273 | 780 | 1400 | 55 | 82 | 1020 | 1945 |
| .50 PMF | 282 | 390 | ·105 | 410 | 810 | 1550 | 158 | 274 | 1355 | 2624 |
| .75 PMF | 1120 | 1435 | 525 | 785 | 936 | 1134 | 238 | 462 | 2819 | 3816 |
| .75 PMF* | 2430 | 3026 | 1240 | 1465 | 1600 | 1620 | 520 | 920 | 5790 | 7031 |

*Dam failure at threshold flood

STEP 11 - Display Existing Condition Results and Propose Additional Action

Purpose

The previous steps have estimated increments in economic losses and probable PAR, TP, and LOL from the threshold flood dam failure compared to the situation if the dam hadn't failed as well as losses from lesser floods. The purpose of STEP 11 is to summarize the extent of the existing condition dam safety hazard. At the same time, this will provide summary documentation of the reasons for considering dam safety modifications.

Present Results and Propose Action

The primary results from the previous steps are in Table III-8, the economic losses, Table III-11, the probable PAR, and the description of the TP and LOL. These should be reiterated in this step emphasizing the increment in the economic losses and probable LOL from the dam failure at the threshold flood compared to losses without failure at the threshold flood. If there is a significant increment in economic losses or probable LOL due to dam failure, additional study of alternatives to reduce the extent of the dam safety hazard is warranted under Phase I analysis. If there is no significant increment in economic losses or LOL from dam failure at the threshold flood, however, hazard reducing alternatives should be evaluated as a Phase II dam safety study. This may be particularly relevant if it is determined that the impacts of the loss of project outputs, such as water supply or hydropower, would be severe.

STEP 12 - Identify Alternatives to Reduce the Dam Safety Hazard to People and Property

Purpose

STEP 11 provided summary documentation that the threshold flood presents a significant hazard to lives and property compared to lesser flood events. The hydrologic deficiency of the dam, therefore, warrants consideration of action to reduce the likelihood and/or consequences of the hazard. The purpose of STEP 12 is to identify the safety improving alternatives. Different scales or levels of design safety for each alternative proposed should be evaluated. These scales of alternatives should be in increments in design flood events up to and including the PMF event.

Key Considerations

1. What alternatives should be considered for further analysis?

The alternatives considered for further analysis should all be physically feasible to implement. For hydrologically deficient dams, alternatives could include: 1) adding spillway capacity including gated spillways; 2) raising the crest of the dam; 3) hardening the dam face; 4) lowering the spillway crest; 5) improvement of reservoir monitoring and emergency warning system and evacuation plans; 6) permanent relocation of downstream activities and population; 7) construction of additional upstream or downstream reservoirs; 8) reallocation of reservoir storage; 9) a combination of the above structural and nonstructural measures.

2. What scales of the structural measures should be considered?

Scales of alternatives should be evaluated to design against not only a PMF event, but also, lesser events. For instance, if the threshold flood is .75 PMF, scales of dam safety alternatives could be considered for .85, .95 and 1.00 PMF events. Additionally, evaluating safety modification for events less than the PMF allows each decision maker to make an independent decision about when the with and without failure hazard is significant.

STEP 13 - Evaluate the Costs of BSC Modification Alternatives.

Purpose

STEP 13 and STEP 14 will be used to establish the BSC design level, defined previously (See Introduction), for dam safety modifications in STEP 15. The BSC will be determined at some level from the threshold flood (some proportion of the PMF) up to the PMF event. The purpose of STEP 13 is to evaluate the economic costs of the alternative modifications, identified in STEP 12, to reduce the hazards from the threshold flood and larger floods up to the PMF.

Key Considerations

What costs should be included?

All structural measures entail construction costs. These should be estimated using standard engineering design and construction cost evaluation methods.

Costs of Alternative Designs

The costs of alternatives identified in STEP 12 should be evaluated for the chosen flood events from the threshold flood up to the PMF. In addition, it is possible that additional combinations of structural measures may be identified and evaluated. Special consideration should be given to those alternatives that do not impose additional downstream hazards from flood events less than the threshold flood. For instance, simply widening the spillway may impose additional downstream hazards from flood events less than the threshold flood compared to the existing condition. Thus, under these circumstances, raising the dam, if the construction costs are not significantly different than widening the spillway, would be preferred. It must be recognized, however, that if the raised dam fails, the failure flood will likely result in greater economic losses and LOL than failure of the existing dam.

The results of the cost evaluation of alternatives, including an improved monitoring system and warning and evacuation plan should be displayed for comparison. The costs of enhancing the monitoring system and warning and evacuation plans should include construction (e.g. remote upstream gauges), annual O&M as well as the costs of implementing the warning and evacuation plan in an emergency. Table III-12 shows an example of the display of the modification costs.

Table III-12

Costs to Modify Project to Accommodate Specified Floods
(in thousands of 1985 dollars)

| Flood Events | Widen Spillway | | | Raise Dam | | | Combinations | | | | Enhanced Warning System and Evacuation Plan | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Cost | | | Cost | | | | Cost | | Cost | |
| | Increment in Width (feet) | Construct | Increased An. O&M | Increment in Height (feet) | Construct | Increased An. O&M | Increment in Width (feet) | Increment in Height (feet) | Construct | Increased An. O&M | Installation | O&M |
| .85 PMF | +125 | $2,500 | $10 | +2 | $1,200 | $50 | +50 | +1 | $1,900 | $40 | $500 | $50 |
| .95 PMF | +410 | $9,800 | $15 | +5 | $3,600 | $85 | +200 | +2 | $5,500 | $60 | $500 | $50 |
| 1.00 PMF | +500 | $12,000 | $20 | +6 | $8,500 | $100 | +300 | +3 | $10,000 | $100 | $500 | $50 |

## STEP 14 - Evaluate Alternatives in Terms of Their Effectiveness in Reducing the Hazard

### Purpose

The purpose of STEP 14 is to evaluate the hazard reduction effectiveness of the alternatives and different scales of alternatives identified in STEP 12. This information will be used to establish the Base Safety Condition (BSC) in STEP 15. From the current Corps policy on modifications to hydrologically deficient dams, the BSC is the smallest design inflow flood event for which there would be in no significant increment in economic losses or LOL from dam failure compared to the dam passing the BSC flood safely. If the increment in losses (fatalities and/or economic) is significant even at the PMF, the PMF should be selected as the BSC. Therefore, after the dam safety modifications are in place there will be no significant difference in economic losses or LOL with and without failure from the BSC flood event or from larger events up to the PMF.

### Key Considerations

1. Should floods less than the threshold flood be considered in evaluating the reduction in the dam safety hazard?

Some alternatives, particular spillway widening, will increase downstream flood flows from events less than the threshold flood. This can increase the downstream hazard from lesser floods compared to the existing conditions. The implication is that a modification that increases flows from lesser floods is trading-off increases in lesser, non-life threatening flood consequences for a reduction in the likelihood of dam failure. Routing these lesser floods through the modified dam identifies the extent of the tradeoff.

2. How should the effectiveness of warning and evacuation be evaluated?

Warning and evacuation is designed to reduce the dam failure hazard primarily to the downstream PAR. Evaluating the effectiveness of warning and evacuation for reducing potential fatalities requires considerable professional judgment. The same considerations in the determination of warning time noted in STEP 9 should be included in evaluating the ability of warning to reduce the potential threatened population and loss of life from failure events. The current research into this area should provide models and methods for evaluating the effectiveness of warning and evacuation. In the meantime, the assumptions about the initiation of warning, professional judgement about the impact of unique conditions and the subjective estimates about evacuation potential ought to be presented in narrative form to serve as a basis for analysis.

3. Should a warning system and evacuation plan be considered in combination of all structural measures?

The effectiveness of structural measures to reduce the dam safety hazard should be evaluated considering the best evacuation that can be expected with the existing warning and evacuation plans in operation as well as with an enhanced warning and evacuation plan. This allows evaluation of the incremental contribution of an enhanced warning and evacuation plan to reducing losses compared to the structural measure alone.

Evaluation of Alternatives

The method for evaluating the dam safety hazard reduction follows the steps used to evaluate the existing level of dam safety followed in STEPS 3-11. Each of the scales of alternatives should be chosen to safely pass intermediate floods greater than the threshold flood up to the PMF. The end result of the process yields estimates of the adverse economic consequences and loss of life of each of the "with" modification floods as well as lesser floods, where applicable (See Key Considerations (1) above).

The results of the evaluation of the effectiveness of alternatives for reducing the dam safety hazard should be displayed as shown in Tables III-13 and III-14. Table III-13 displays the probable PAR for various flood event and structural modification combinations, also with and without warning and evacuation plans. In this case, the probable PAR could be considered to be significantly greater with dam failure than without failure for all structural modifications with design safety less than the PMF event.

Table III-14 shows the economic flood losses from various flood events and compares these losses to those incurred with alternative scales of safety modification. Included in the comparison is an evaluation of the effectiveness of warning and evacuation plans in reducing economic losses. It is assumed that the warning allows the PAR to remove some personal belongings and vehicles from the threatened area. For this example it was assumed that warning reduced property losses by 10%. Current research should provide a basis refining this estimate. Note that widening the spillway increases economic losses from flooding events less than the threshold flood compared to the existing spillway size (Table III-14(a)). Again in this instance, the economic losses could be considered to be significantly greater with dam failure than without failure for all structural modifications with design safety less than the PMF event. Note that raising the dam increases the failure economic losses and PAR from events greater than the threshold flood compared to the existing dam height. Also note that although Tables III-13 and III-14 show failure and nonfailure PAR's and economic losses for flood events greater than the modification design level, these values are not used in Phase I. The relevant values are those above the bold line shown in the tables. They will be necessary for Phase II, if Phase II analysis is desired. Finally note that although failure economic losses and PAR are shown for a PMF event with a PMF design, it is assumed that the dam will not fail from a PMF with a PMF design level. These values will be needed, however, to complete the curves shown in Figures III-7 and -8.

Any other structural or nonstructural dam safety modification identified in STEP 10, should be evaluated and displayed in a similar manner.

Table III-13 (a)

Probable PAR with and without Enhanced Warning and Evacuation Plans
Widen Spillway Alternative

| Flooding Events | .75 PMF Existing (720 feet) Failure PAR Without Warning | .75 PMF Existing (720 feet) Failure PAR With Warning* | .75 PMF Existing (720 feet) PAR Without Failure | .85 PMF (845 feet) Failure PAR Without Warning | .85 PMF (845 feet) Failure PAR With Warning* | .85 PMF (845 feet) PAR Without Failure | .95 PMF (1130 feet) Failure PAR Without Warning | .95 PMF (1130 feet) Failure PAR With Warning* | .95 PMF (1130 feet) PAR Without Failure | 1.00 PMF (1220) Failure PAR Without Warning | 1.00 PMF (1220) Failure PAR With Warning* | 1.00 PMF (1220) PAR Without Failure |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| .10 PMF | N/A | N/A | 0 | N/A | N/A | 0 | N/A | N/A | 0 | N/A | N/A | 0 |
| .25 PMF | N/A | N/A | 4910 | N/A | N/A | 5200 | N/A | N/A | 5400 | N/A | N/A | 5450 |
| .50 PMF | N/A | N/A | 19810 | N/A | N/A | 20400 | N/A | N/A | 20700 | N/A | N/A | 20750 |
| .75 PMF | 37650 | 1883 | 21000 | N/A | N/A | 21200 | N/A | N/A | 21300 | N/A | N/A | 21400 |
| .85 PMF | 37800 | 1890 | 21500 | 37800 | 1890 | 21600 | N/A | N/A | 21700 | N/A | N/A | 21700 |
| .95 PMF | 37800 | 1890 | 21600 | 38000 | 1900 | 21700 | 38000 | 1900 | 21800 | N/A | N/A | 21800 |
| 1.00 PMF | 38000 | 1900 | 22000 | 38000 | 1900 | 22200 | 38200 | 1910 | 22000 | 39000** | 780** | 22000 |

*Threatened Population is the PAR with warning.
**At a PMF design the dam will not fail from a PMF event.
The failure PAR, however, is required to complete the figures.

Table III-13(b)

Probable PAR with and without Warning and Evacuation Plans
Raise Dam Alternative

| Flooding Events | .75 PMF Existing | | | .85 PMF (existing + 2 feet) | | | .95 PMF (existing + 5 feet) | | | 1.00 PMF (existing + 6 feet) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Failure | | | Failure | | | Failure | | | Failure | | |
| | PAR Without Warning | PAR With Warning* | PAR Without Failure | PAR Without Warning | PAR With Warning* | PAR Without Failure | PAR Without Warning | PAR With Warning* | PAR Without Failure | PAR Without Warning | PAR With Warning* | PAR Without Failure |
| .10 PMF | N/A | N/A | 0 | N/A | N/A | 0 | N/A | N/A | 0 | N/A | N/A | 0 |
| .25 PMF | N/A | N/A | 4910 | N/A | N/A | 4910 | N/A | N/A | 4910 | N/A | N/A | 4910 |
| .50 PMF | N/A | N/A | 19810 | N/A | N/A | 19810 | N/A | N/A | 19810 | N/A | N/A | 19810 |
| .75 PMF | 37650 | 1883 | 20700 | N/A | N/A | 20700 | N/A | N/A | 20700 | N/A | N/A | 20700 |
| .85 PMF | 37800 | 1890 | 21500 | 38500 | 1925 | 20800 | N/A | N/A | 20800 | N/A | N/A | 20800 |
| .95 PMF | 37800 | 1890 | 21600 | 39000 | 1950 | 21400 | 42000 | 2100 | 21000 | N/A | N/A | 21000 |
| 1.00 PMF | 38000 | 1900 | 22000 | 41000 | 2050 | 21800 | 43000 | 2150 | 21500 | 45000** | 900** | 21200 |

*Threatened Population is the PAR with warning.
**At a PMF design the dam will not fail from a PMF event.
The failure loss, however, is required to complete the figures.

Table III-14 (a)

Downstream

Flood Losses with and without Warning and Evacuation

Widen Spillway Alternative

| Flooding Events | .75 PMF Existing (720 feet) Failure Losses Without Warning | .75 PMF Existing (720 feet) Failure Losses With Warning | .75 PMF Existing (720 feet) Nonfailure Losses W/O Warn. | .85 PMF (845 feet) Failure Losses Without Warning | .85 PMF (845 feet) Failure Losses With Warning | .85 PMF (845 feet) Nonfailure Losses W/O Warn. | .95 PMF (1130 feet) Failure Losses Without Warning | .95 PMF (1130 feet) Failure Losses With Warning | .95 PMF (1130 feet) Nonfailur Losses W/O Warn. | 1.00 PMF (1220 feet) Failure Losses Without Warning | 1.00 PMF (1220 feet) Failure Losses With Warning | 1.00 PMF (1220 feet) Nonfailur Losses W/O Warn. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| .10 PMF | N/A | N/A | $0 | N/A | N/A | $0 | N/A | N/A | $0 | N/A | N/A | $0 |
| .25 PMF | N/A | N/A | $85 | N/A | N/A | $88 | N/A | N/A | $92 | N/A | N/A | $95 |
| .50 PMF | N/A | N/A | $260 | N/A | N/A | $280 | N/A | N/A | $290 | N/A | N/A | $295 |
| .75 PMF | $916 | $870 | $330 | N/A | N/A | $340 | N/A | N/A | $360 | N/A | N/A | $365 |
| .85 PMF | $922 | $876 | $380 | $925 | $879 | $382 | N/A | N/A | $385 | N/A | N/A | $388 |
| .95 PMF | $925 | $879 | $410 | $928 | $882 | $415 | $932 | $885 | $418 | N/A | N/A | $420 |
| 1.00 PMF | $928 | $882 | $430 | $932 | $885 | $432 | $935 | $888 | $433 | $935 * | $888 * | $435 |

* At a PMF design the dam will not to fail from a PMF event.
The failure loss, however, is required to complete the figures.

Table III-14 (b)
Downstream
Flood Losses with and without Warning and Evacuation
Raise Dam Alternative

| Flooding Events | .75 PMF Existing | | | .85 PMF (existing + 2 feet) | | | .95 PMF (existing + 5 feet) | | | 1.00 PMF (existing + 6 feet) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Failure | | | Failure | | | Failure | | | Failure | | |
| | Losses Without Warning | Losses With Warning | Nonfailure Losses W/O Warn. | Losses Without Warning | Losses With Warning | Nonfailure Losses W/O Warn. | Losses Without Warning | Losses With Warning | Nonfailur Losses W/O Warn. | Losses Without Warning | Losses With Warning | Nonfailur Losses W/O Warn. |
| .10 PMF | N/A | N/A | $0 | N/A | N/A | $0 | N/A | N/A | $0 | N/A | N/A | $0 |
| .25 PMF | N/A | N/A | $85 | N/A | N/A | $85 | N/A | N/A | $85 | N/A | N/A | $85 |
| .50 PMF | N/A | N/A | $260 | N/A | N/A | $260 | N/A | N/A | $260 | N/A | N/A | $260 |
| .75 PMF | $916 | $824 | $328 | N/A | N/A | $328 | N/A | N/A | $328 | N/A | N/A | $328 |
| .85 PMF | $922 | $830 | $380 | $962 | $866 | $358 | N/A | N/A | $358 | N/A | N/A | $358 |
| .95 PMF | $925 | $833 | $410 | $974 | $877 | $402 | $1,007 | $906 | $385 | N/A | N/A | $385 |
| 1.00 PMF | $928 | $835 | $430 | $983 | $885 | $422 | $1,022 | $920 | $414 | $1020 * | $918 * | $400 |

* At a PMF design the dam will not fail from a PMF event.
The failure loss, however, is required to complete the figures.

STEP 15 - Determination of the Base Safety Condition (BSC)

Purpose

The purpose of STEP 15 is to combine the information generated in STEPS 13 and 14 to establish the BSC.

The BSC

The base safety condition (BSC) flood event is that flood where there is no significant increase in adverse consequences from dam failure compared to non-failure adverse consequences. That is, there is no significant increase in loss of life and/or economic losses from dam failure compared to without dam failure from the BSC inflow flood event. If failure always results in a significant increase in losses, regardless of the inflow event, the design flood event chosen for safety modification design purposes should be the PMF.

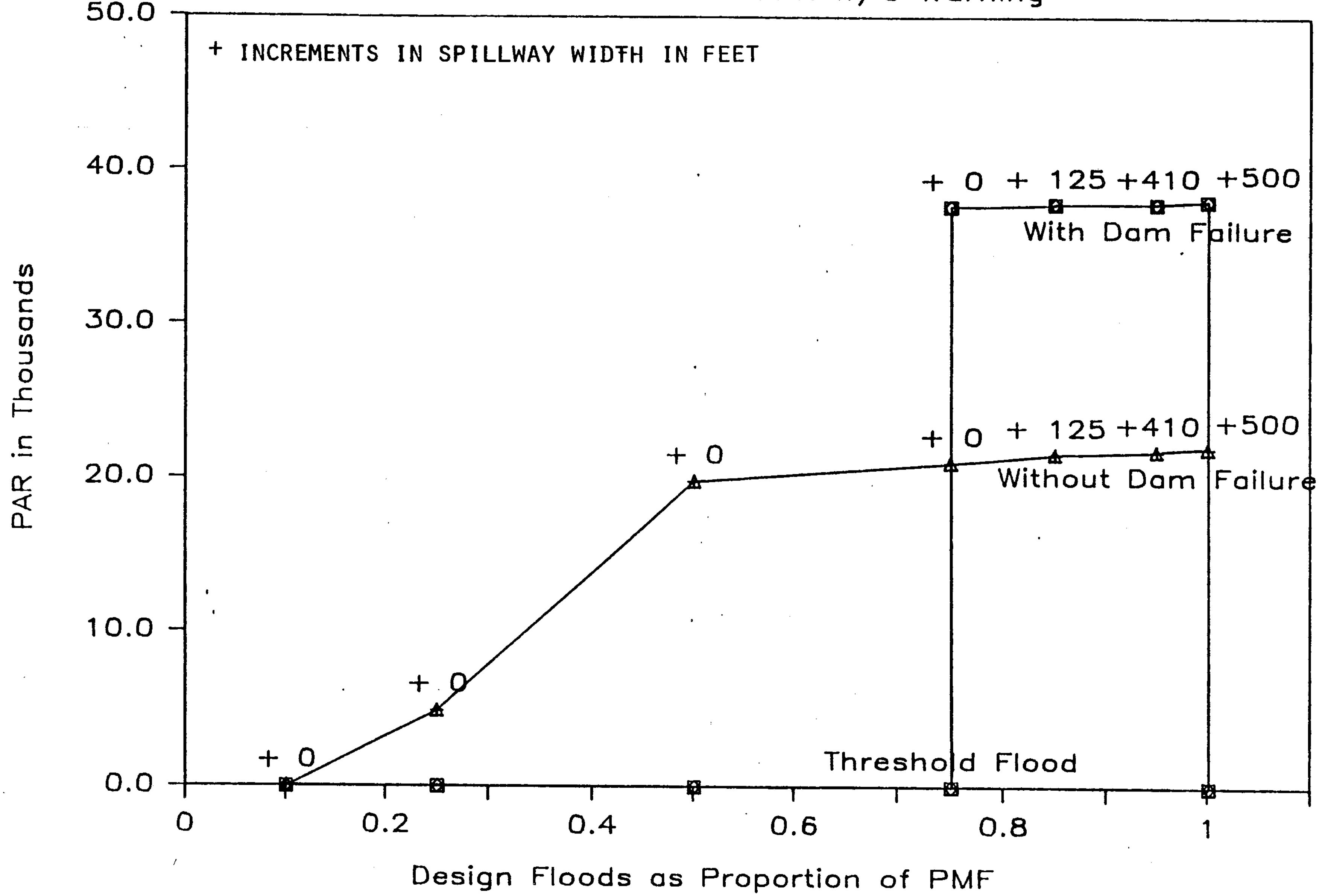
Figures III-7 and III-8, based on Tables III-13 and III-14 provide an example for displaying the establishment of the BSC. These tables show the increment in PAR and economic losses from dam failure compared to without dam failure for the threshold flood and each intermediate flood up to the PMF. At each flood event, the hazard to lives and property is evaluated assuming that the safety modification that can just pass the flood is in place.

In this example, the BSC condition could be established as the PMF. In addition, a structural measure combined with enhanced warning and evacuation may be chosen because of the large residual PAR without a warning plan.

It is possible that the evaluation of alternatives may establish the BSC at less than the traditional PMF modification design standard. For instance, Figures III-9 and III-10 show an alternate possible result from the evaluation of alternatives. In this example, the threshold flood is .50 PMF. The evaluation of modification of alternatives following STEPS 1-15 reveals that all flood events greater than the .85 PMF may produce equivalent with failure and without failure economic losses and PAR's. In this case, the .85 PMF could establish the BSC design event for safety modification. Any modifications to design against larger flood events do not reduce the extent of the hazard. That is, for any modification alternative-design flood combination greater than .85 PMF, there is no increase in economic losses and PAR's from dam failure compared to without dam failure. It is possible, however, that a .75 PMF BSC design could also be considered to result in no significant difference in the with and without hazard.

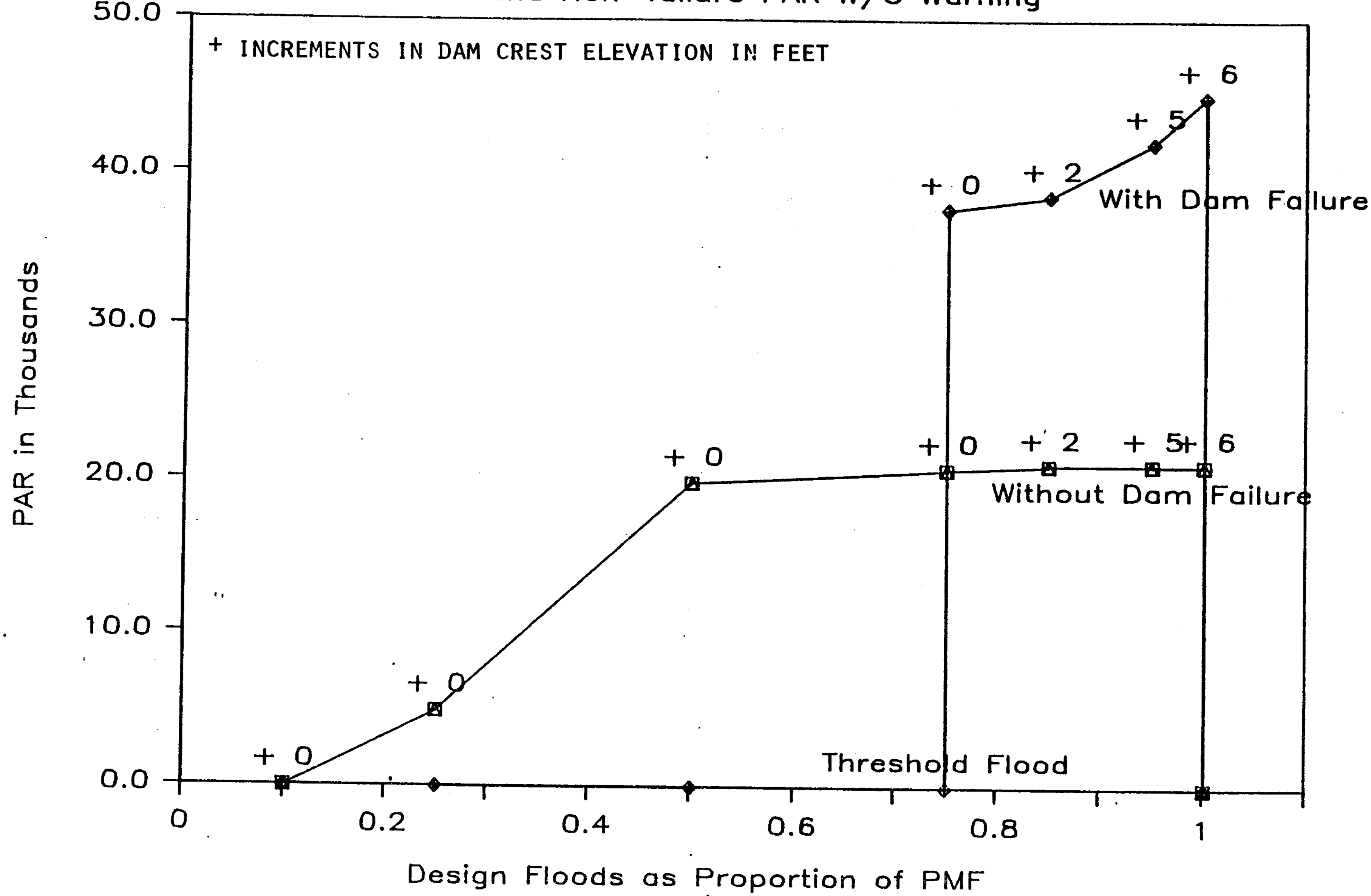
# Figure III–7 (a)

Failure and Non–failure PAR W/O Warning



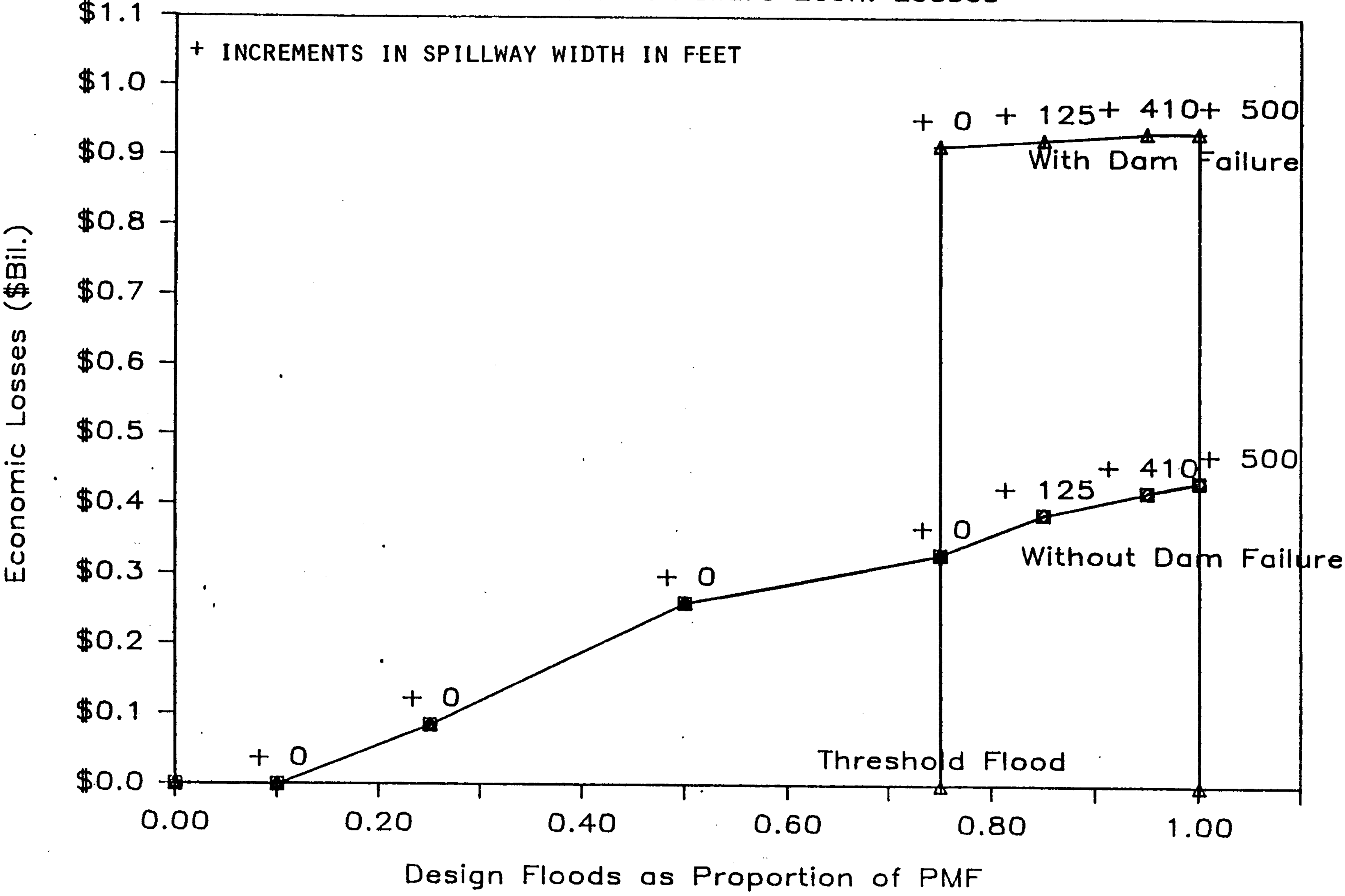
# Figure III—7 (b)

Failure and Non—failure PAR W/O Warning



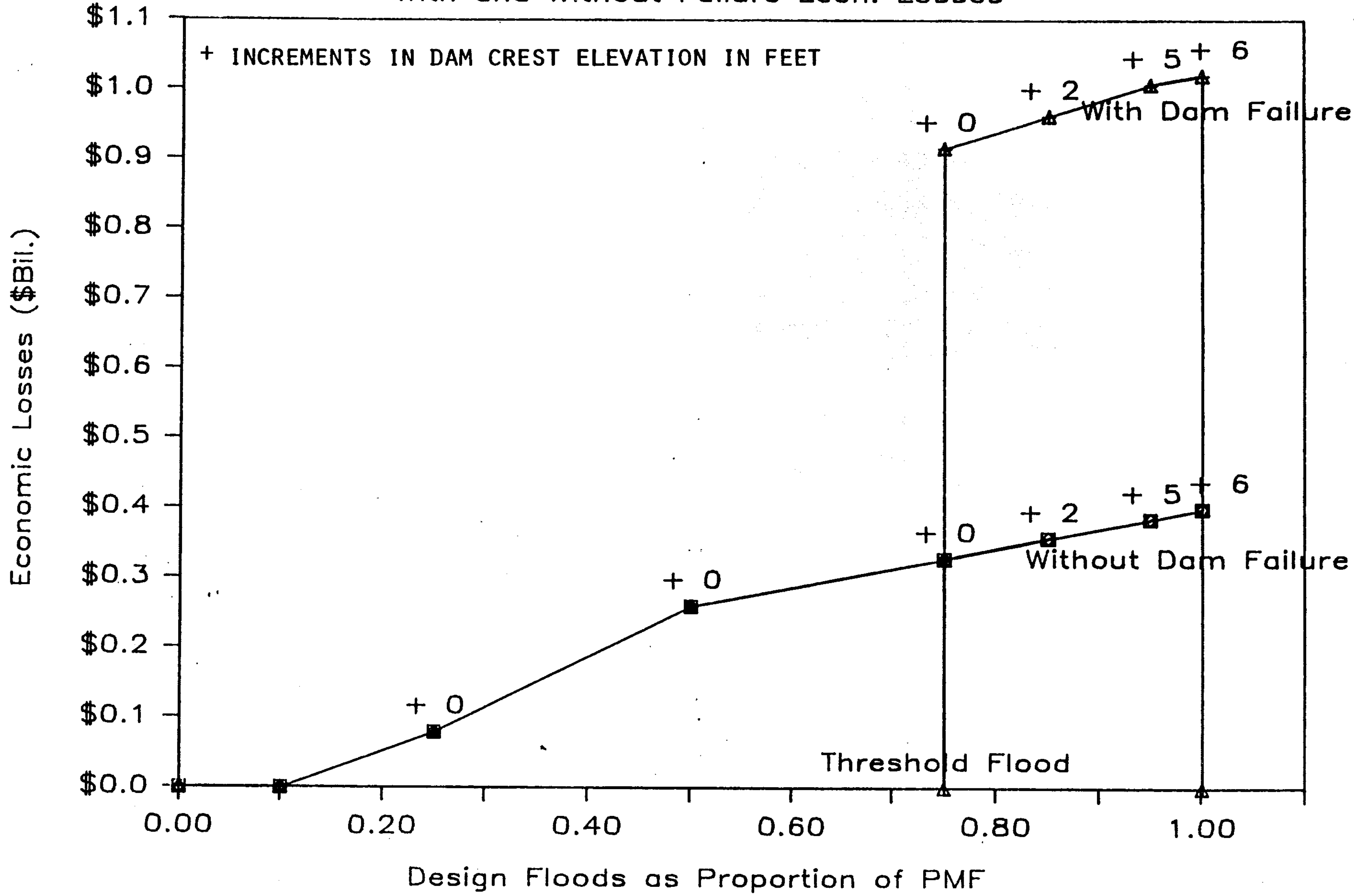
# Figure III—8(a)

With and Without Failure Econ. Losses



# Figure III—8(b)

With and Without Failure Econ. Losses



In the example shown in Figures III-9 and III-10, a recommendation of safety modifications for events greater than .85 PMF, in general, requires the complete probabilistic analysis of Phase II. Special circumstances such as small incremental costs of providing PMF safety or future growth, however, may provide justification for moving the BSC to the PMF within Phase I. If future growth, particularly in the PAR, is well supported and would justify moving the BSC to a larger design flood, the conditions and trends supporting the future growth estimate may be described and placed in the report.

As noted in the DAEN-CW/DAEN-EC policy letter of 8 April 1985 (Appendix B), there is currently no clear criterion for establishing when the difference in the "with and without" failure hazard is significant. Therefore, the material provided in the dam safety modification report must be sufficient to "...permit others in the decision chain to reach independent conclusions" about the base safety condition.

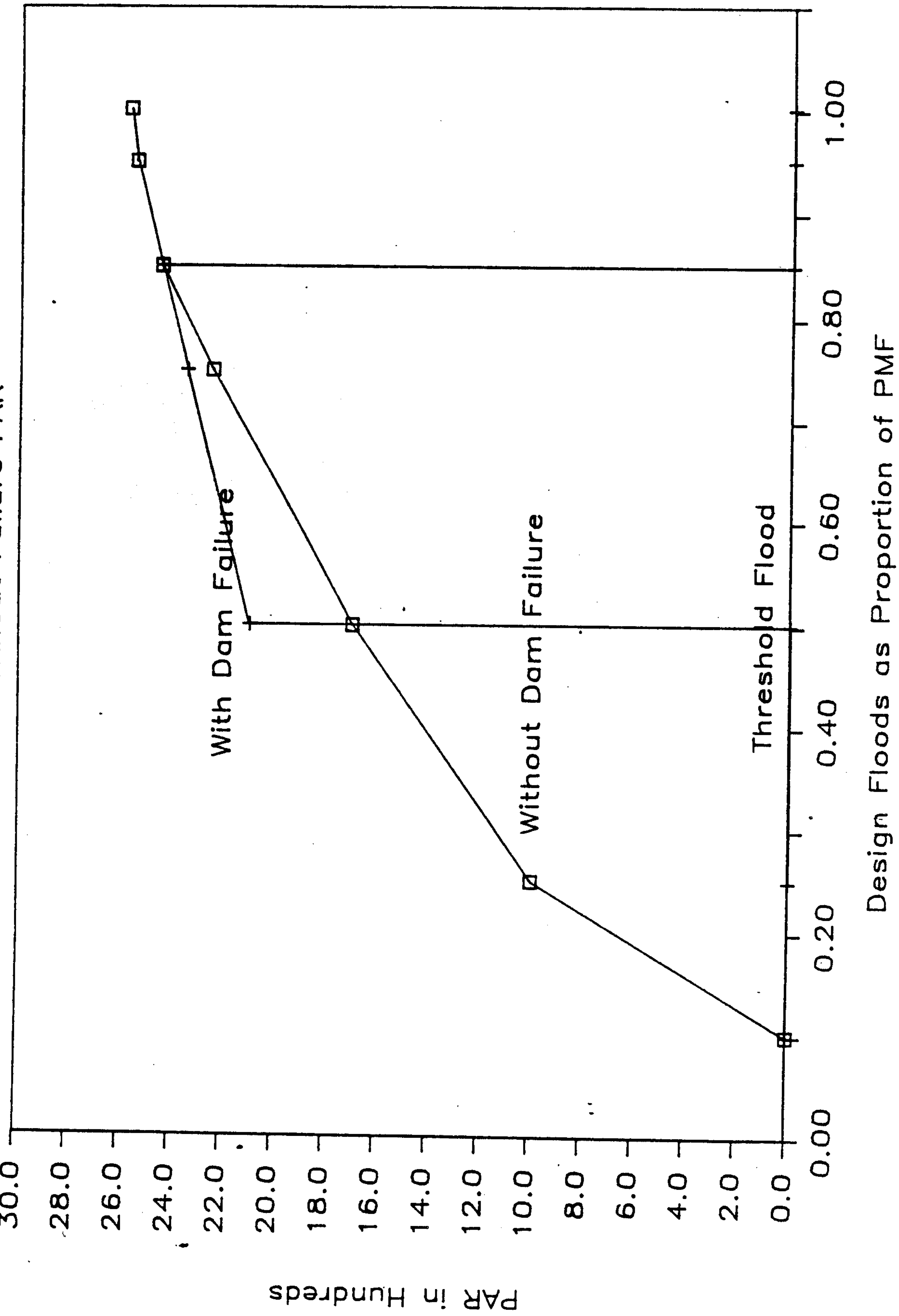
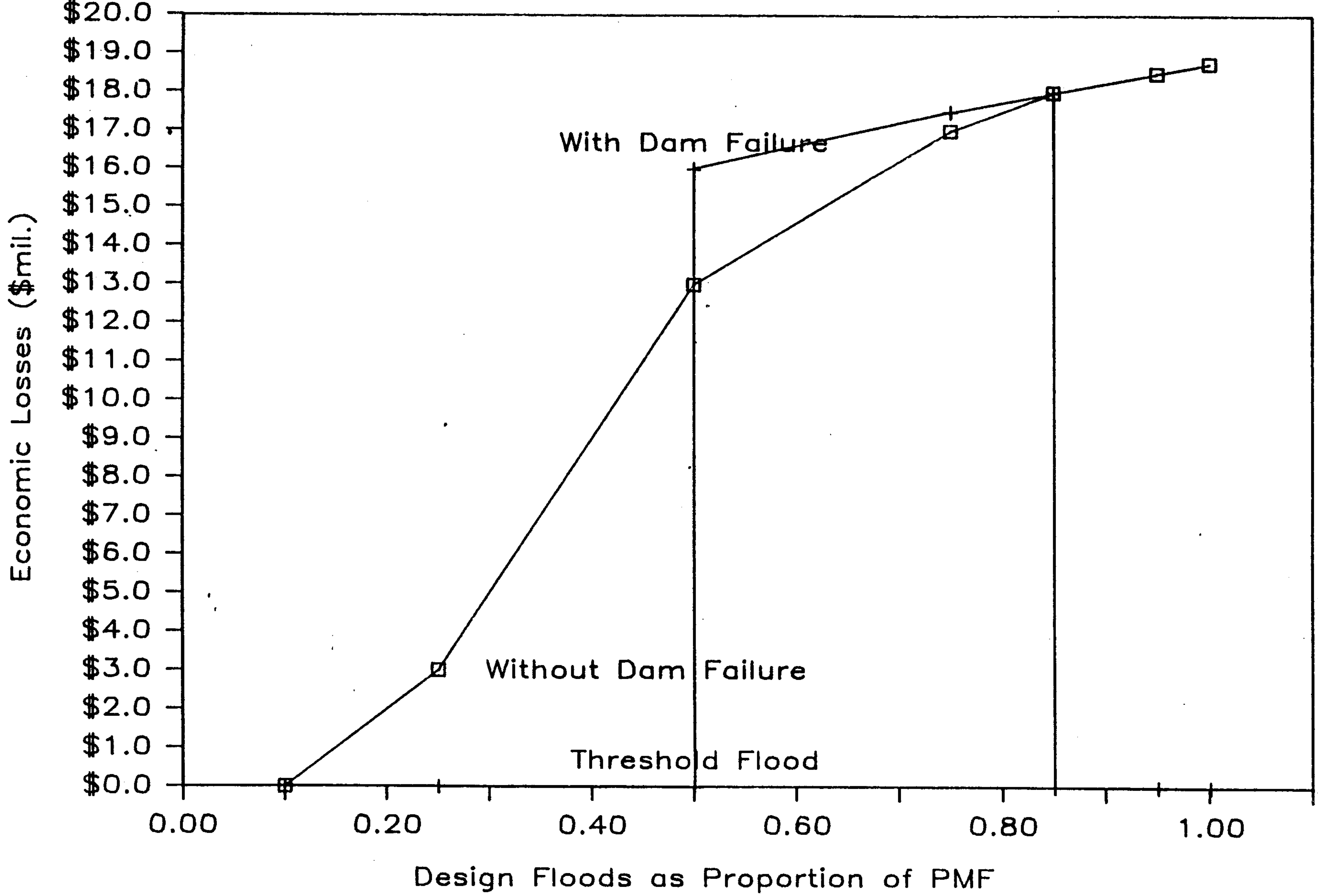



Figure III—9
With and Without Failure PAR

# Figure III—10

Failure and Non—Failure Economic Losses



## STEP 16 - Recommend Choice of Alternative to Meet BSC

### Purpose

The purpose of STEP 16 is to provide a summary display of the documentation of the evaluation process and to recommend a dam safety modification for implementation. In general, the analysis conducted within STEP 15 will define the most cost effective rehabilitation alternative or combination of alternatives, unless there are special circumstances.

### Key Considerations

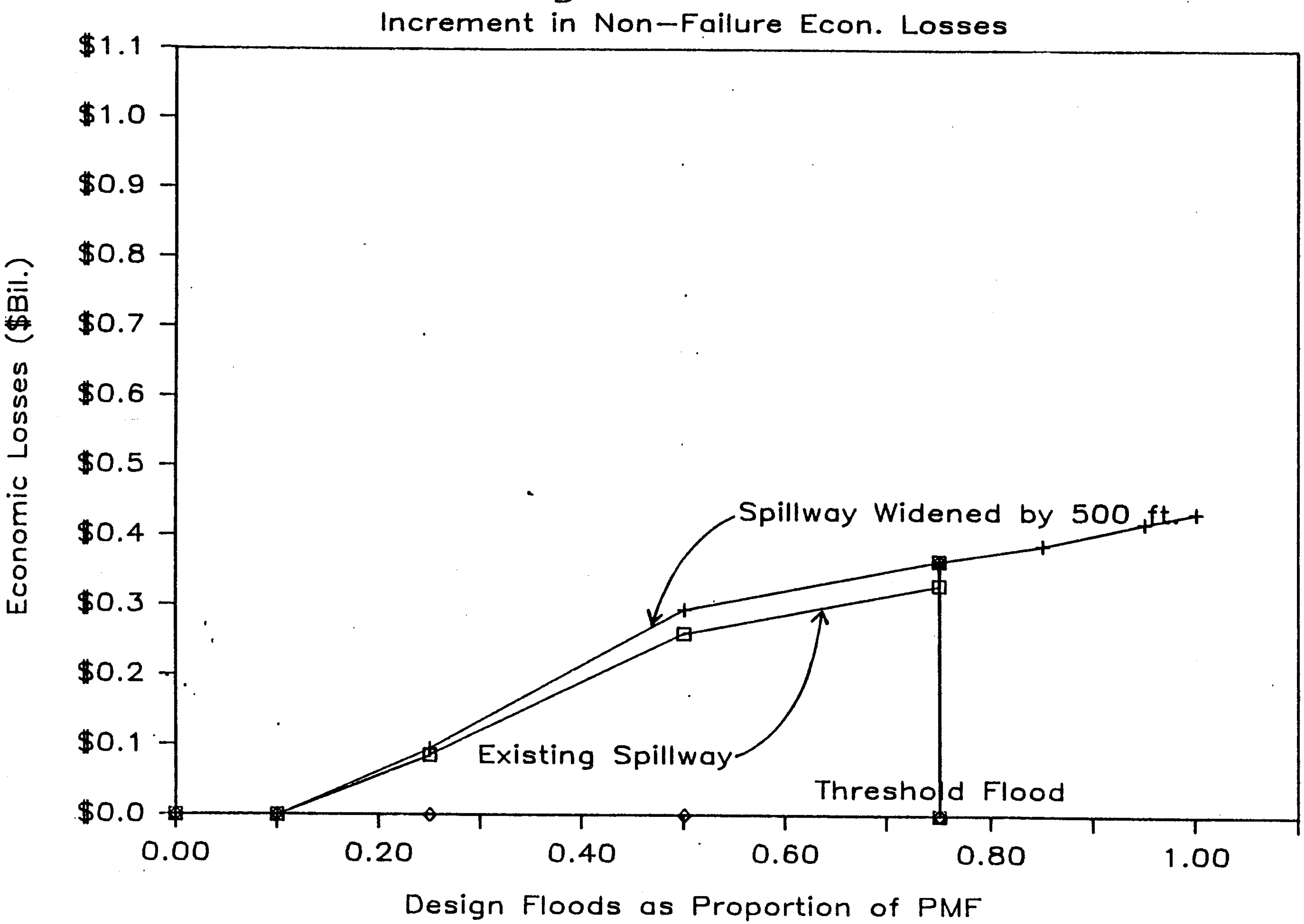
Must the lowest cost alternative of meeting the BSC be recommended?

In general, the lowest cost alternative identified in STEP 13 should be recommended for implementation. Some special circumstances may allow for the recommendation of a higher cost alternative, however. These special circumstances may cover a situation where the emergency operations with the lowest cost alternative increase the upstream or downstream hazard to people and property from non-failure threatening events compared to the existing level of safety design. These could include increases in non-failure economic losses as well as adverse environmental impacts. For example, Figure III-11 shows the difference in residual non-failure downstream economic losses from widening the spillway to safely pass the PMF compared to the existing spillway capacity for the example dam. This difference may be important in the decision of whether to widen the spillway as a dam safety modification.

### Documentation of the Choice of Alternatives

The end result of Phase I analysis is a decision document describing the problem, the results of the evaluations and a recommendation supported by the information presented. This process basically requires a summarization and display of the process and results of the previous steps. The important summary tables prepared in each step should be shown. These should document the existing condition safety problems, describe the establishment of the BSC as well as the costs of achieving the BSC. Any critical assumptions used in the analysis should be reiterated and supported. This document should also contain a reiteration of: 1) the probable PAR "with" and "without" the proposed modification (Table III-13 and Figure III-7); 2) the economic losses "with" and "without" the proposed modification (Table III-14 and Figures III-8 and III-11); and; 3) the alternative costs to modify the project (Table III-12). The discussion of the chosen alternative should provide the rationale supporting the recommendation, compared to those not recommended.

# Figure III—11



STEP 17 - Determination of Whether Breaching the Dam Should Be Evaluated as an Alternative

Purpose

One final component of the dam safety modification decision document is the determination of the overall economic merit of the modification proposed in STEP 16. The basic criterion is that the benefits of continued operation of the project should exceed the modification cost of the project. If the benefits of the modified project are less than the modification costs plus annual operation and maintenance cost of the modified project, consideration must be given to breaching the dam. Breaching the dam, however, incurs costs which must also be used in determining the option recommended.

Evaluation of Breaching the Dam as an Alternative

The benefits of various component outputs of the existing project, e.g. flood control, hydropower, water supply, etc., must be evaluated and the impact of the proposed modification on these benefits estimated. In some instances, the with and without modification project benefits will be the same. If the proposed modification increases or decreases project benefits, the source and value of those increments or decrements must be identified and estimated.

The proposed modification may increase or decrease the annual operation and maintenance costs of the project. These should be identified and value estimates provided.

The proposed modification costs, changes in O&M costs and modified project benefits should be adjusted to an average annual basis using a 50 year life and the federal discount rate. These adjusted values should be presented in a summary table such as Table III-15. If the ratio of average annual benefits of the modified project to the total average annual costs is less than 1, an analysis of the costs to breach the dam should be prepared. As provided in the 8 April 1985 policy letter, "[t]he rationale for not selecting the breaching option will be provided if improvement is recommended."

Table 15

Breach Analysis*

| | | |
|---|---|---|
| 1. | Average annual O&M costs of existing project | $1,000,000 |
| 2. | Average annual O&M costs of selected modification | $1,100,000 |
| 3. | Average annual investment cost of selected modification<br>Raise dam 6 feet with first costs of $8,500,000<br>Project Life = 50 years  Interest Rate = 8 3/8% | $725,000 |
| 4. | Total average annual cost of selected modification<br>(item 2 + item 3) | $1,825,000 |
| 5. | Average annual benefits of modified project ** | $19,500,000 |
| 6. | Ratio of project benefits to modification costs<br>(item 5 / item 4) | 10.7 |
| 7. | Cost to breach dam (if item 6 is less than 1.0) | ________ |

** Same as benefits for existing project unless the proposed modification

# SECTION IV - PHASE II GUIDELINES

# SECTION V - APPENDICES

(Appendix A thru E)

# APPENDIX A

## Background Discussion of Dam Safety/Risk Analysis Policy Development

DAM SAFETY/RISK ANALYSIS

POLICY DEVELOPMENT

## 1. BACKGROUND

The National Dam Safety Inspection Program uncovered thousands of unsafe publicly and privately owned dams. The surveys were based on fairly rudimentary and qualitative criteria and engineering judgement. Among the 3000 or so dams identified as potentially unsafe were a number of Corps dams. These Corps dams were not unsafe because of any structural faults, but rather because external conditions affecting the dam had changed since construction. These included better rainfall information and hydrologic data upon which computation of extreme flood events were based. The potential for downstream dam failure hazards also increased through growth in downstream population and economic development. Although most of the Corps dams under consideration performed adequately according to the original design specifications and conditions based on planning projections, they no longer met the current design standards.

The potential fiscal and budgetary consequences of rehabilitating these dams to meet current hydrologic conditions and engineering design standards were substantial. Because of these concerns, the Office of the Assistant Secretary of the Army for Civil Works required that a uniform approach to dam safety (reliability) evaluation be developed. The general intent of the approach was an acknowledgement of or explicit consideration of the risk of dam failure due to hydrologic causes, both in terms of economic costs and loss of life.

Since little was known about the practice of risk analysis, Assistant Secretary of the Army William R. Gianelli concluded his request for risk analysis by asking for "a substantial program of research which addresses the issue of dam safety assurance for existing structures as it relates to the criteria used for spillway design," (letter of 28 Sept., 1983, Appendix B). The request specified that, as part of a "well-ordered spillway design process," the following factors needed to be considered explicitly:

(1) "The relationship of the largest recorded floods in the watershed as well as in the general area of the project to any proposed spillway design flood;

(2) "The projected frequency of occurrence of the proposed spillway design flood;

(3) "The risk reductions to be derived from proposed spillway reconstruction expenditures in the interest of dam safety assurance;

(4) "Whether or not downstream beneficiaries can afford to pay the cost of full flood control protection and what options should be provided to them assuming they will be called upon to defray a portion of the costs; and

(5) "Is there a relationship between the degree of flood control

which should be provided without regard to who pays for the costs of the dam and reservoir."

Secretary Gianelli's letter of 28 September 1983 and subsequent correspondence with OCE set three major activities into motion:

(a) A study by the National Research Council's (NRC) "Committee on Safety Criteria for Dams", jointly sponsored by the Corps of Engineers and the Bureau of Reclamation.

(b) The development of a Corps "Policy for Evaluating Modifications of Existing Dams Related to Hydrologic Deficiencies." (DAEN-CW/DAEN-EC letter of 8 April, 1985). [Appendix C]

(c) Initiation of a research program at the Institute for Water Resources and Hydrologic Engineering Center on dam safety risk analysis for hydrologically deficient dams.

## 2. NATIONAL RESEARCH COUNCIL'S REPORT ON "SAFETY OF DAMS"

The Corps and Bureau sponsored study by the NRC Committee on Safety Criteria for Dams was completed in January, 1985. The report, entitled "Safety of Dams: Flood and Earthquake Criteria", influenced both the formulation of Corps policy and the direction of the research program. The Corps' policy was to a large extent dictated by practical considerations and the need to evaluate a current inventory of hydrologically deficient dams with a sparse information base and very rudimentary risk analysis concepts and techniques. The procedures within the policy reflected the need to make on-going decisions on dam rehabilitation proposals, while integrating the results of the risk analysis research program in a series of stages, tied to the annual budget justification.

The NRC Committee recommended an approach to risk-based analysis for dam rehabilitation (NRC, 1985; Appendix E, pg. 244):

> "A risk-based analysis needs to consider the consequences and costs of reservoir operation (including damages from high lake levels and discharge, and also damage to the dam and from interruption of services) and the relative likelihood of such events. In general, four metrics are used to describe the consequences for each alternative considered:
>
> 1. likely loss of life;
> 2. economic damages from lake levels, releases, and damage to the dam;
> 3. the cost of actions associated with each modification of the dam, reservoir, and associated channels and any flood warning system; and
> 4. the cost of discontinued or interruptions in service due to damage to or the failure of the dam because of an extraordinary hydrologic event."

However, the NRC Committee also recognized that in order to conduct risk-cost analyses, estimates of probable frequencies of extreme flood events would be required, along with other explicit probability distribution functions for other loading and resistance factors, as well as economic benefits and costs. The NRC Committee sought ". . .to strike reasonable balances between what is theoretically desirable and what is practical based on current technologies" (pg. 97). Thus, the NRC committee amended their recommendations for risk-based analysis with several important caveats.

First, in considering the range of probable hazards from dam failure, the Committee chose to categorize dams, based on qualitative criteria, into low-, medium- and high-hazard dams. The hazard classifications are based on some combination of measures of the (a) population at risk; (b) likely loss of life; (c) economic losses; and (d) potential dam failure as a proportion of PMF. In reconsidering proposed hydrologic criteria to be used as the basis for a set of evaluation-decision rules in lieu of a formal risk-cost analysis, the NRC Committee found that it was reasonable to separate new and existing high-hazard dams.

The Committee concluded that ". . .retention of the PMF criteria for design of spillways for new dams in high-hazard locations is generally recommended" (pg. 99). In discussing the appropriate evaluation criteria for existing high-hazard dams, the Committee introduced two fundamental and related concepts, the Safety Evaluation Flood (SEF) and the notion of incremental hazard analysis as the basis for determining a "safe" dam. The SEF is defined as the "...largest reasonable hypothetical water inflow for which the safety of a dam ... is to be evaluated." The SEF is essentially the largest possible "non-failure" flood that a dam can hold. The relevant decision criterion for justifying a larger spillway capacity or other dam alteration capable of passing a flood of magnitude up to the PMF, is whether the incremental economic damages and/or loss of life due to dam failure flood are significantly larger than the SEF, or "non-failure" flood. The SEF can also be used as a derived spillway design flood which is based on hypothetical improvements in a dam's capacity to pass large floods to prevent dam failure up to the point at which the increments in "failure" versus "non-failure" damages are minimized.

The SEF is used by the NRC Committee as a substitute risk evaluation criterion, which can be used to compare failure and non-failure consequences relative to two benchmarks, the current threshold failure flood and the PMF. The emphasis on incremental analysis, in effect, constitutes a decision rule, equivalent to selecting a project based on a benefit-cost ratio or based on maximizing net benefits. These two evaluation and decision criteria comprise the basis for the NRC Committee's suggestion for approaching the selection of a spillway design standard for existing high hazard dams.

The NRC Committee proposed these hazard assessment criteria because they concluded that ". . .there is no single, universally correct approach to evaluating the safety of all existing high-hazard dams against extreme floods" (pg. 101). They then postulated a two-step procedure relying on the two criteria to separate existing high hazard dams into two groups. The first group consists of the dams in which the incremental damages of "failure" are much greater than the current "non-failure" damages due to the SEF.

> "If it is reasonably probable that the dam would fail if overtopped and the incremental impact (marginal damages and potential loss of life) clearly would be of such magnitude that potential for overtopping must be eliminated insofar as reasonably possible, adopt the PMF and as the SEF and proceed to develop any needed remedial measures to assure that the SEF may be safely passed with normal allowances for freeboard, etc. (In some situations encroachment on the normal freeboard allowance by the SEF may be considered as acceptable.)" (pg 101)

The second group of dams consisted of those where it wasn't clear whether the remedial work needed to permit the safe passage of a PMF (without dam failure) was justified. That is, the increment in economic damages and loss of life between the SEF and the failure flood was not significantly different to justify moving to the PMF as the design standard. It is reasonable to expect that there would be a number of sound reasons, based on local characteristics (absence of adequate warning time, population concentrations, other unique circumstances) to justify going beyond the SEF, despite the absence of a significant difference between failure and non-failure damages. Under such circumstances, where the consequences of dam failure are determined to be unacceptable regardless of the incremental damages decision rule, then the NRC Committee recommends that risk-based analysis be undertaken. Although, the NRC report does not formally cover the details of such a risk analysis procedure, they provide an example of risk analysis based on that conducted by the Bureau of Reclamation (NRC; Appendix E) for dam safety rehabilitation measures.

## 3. CORPS POLICY

The Corps' policy guidance letter of 8 April 1985 (Appendix C), titled "Policy for Evaluating Modifications of Existing Dams Related to Hydrologic Deficiencies" encompasses most of the NRC committee recommendations discussed previously. A few changes in terminology and the addition of a few specific requirements and more detailed procedures than that offered in the NRC report are all that differentiate the two documents. The evaluation concepts are virtually similar.

Instead of the "Safety Evaluation Flood" (SEF) of the NRC Committee's suggested manner of analysis, the Corps has chosen to call it the "base safety standard" or "condition." The Corps' "threshold flood" is defined as the

". . .flood that fully utilizes the existing structure. . ." The first part of the Corps analysis, then, is to determine at what point the dam would fail under current conditions. The second component of analysis is the determination of a "base safety standard" or "condition" (BSC). The BSC incorporates the notion of using the increment in flood damages as the decision criterion for making a preliminary or first-order assessment of the appropriate spillway design standard.

> "The base safety standard will be met when a dam failure related to hydrologic capacity will result in no significant increase in downstream hazard (loss of life and economic damages) over the hazard that would have existed if the dam had not failed."

The Corps' policy also builds on the NRC Committee's recommendations for a two-category approach to risk analysis. The first category of existing high hazard dams are those for which the incremental damages of the flood that causes dam failure are still significantly greater than the non-failure BSC flood, even when the BSC equals the most currently computed and accepted PMF design criterion. The Corps terms this categorization of dams based on a comparative hazard assessment through incremental economic damages as Phase I analysis. The second category of high-hazard dams are those where the BSC is found to be less than the PMF design criterion. That is, the increment in damages between the "failure" flood and "non-failure" peak spillway flood is found not to be significant at some intermediate point between the threshold flood causing failure under the original design criteria and the newly computed PMF. For these dams, any recommendation for moving beyond the BSC to the PMF must be supported by a formal risk-cost analysis. This stage of analysis is termed Phase II analysis and comprises the more classically defined version of risk analysis.

One of the less well-developed but implicit aspects of the Corps policy is the matter of determining the Base Safety Condition. Developing the BSC requires what are essentially a series of iterations of several possible remedial alternatives (e.g., raising dam, widening spillway, combinations), calculating incremental damages, construction costs and effectiveness in meeting the BSC. Each structural/non-structural modification alternative results in different construction costs, for each increment of size or scale; residual downstream and upstream damages; population at risk; and flood control capability. These alternatives need to be developed as part of planning and design activities for rehabilitation. They are then arrayed to demonstrate the most cost effective measure or series of measures which would reduce the increment between "failure" and "non-failure" damages. The point at which the increment of damages (economic costs and/or loss of life) is no longer considered significant (but less than or equal to the PMF) defines the BSC.

The preliminary procedures for Phase I analysis are developed in detail in Part III of this report, and comprise part of the outputs of the dam safety risk analysis research program conducted by the Institute for Water Resources and the Hydrologic Engineering Center. Procedures for risk analysis required for Phase II dams are currently being studied and developed as part of the case study analysis within the research effort. A framework for Phase II risk analysis, developed by the Bureau of Reclamation has been presented in Appendix E of the National Research Council's report on "Safety Criteria for Dams". This framework would comprise one of the methods examined and developed as part of the risk research program.

The Corps policy also defines more clearly than the NRC report that either economic damages and/or probable loss of life may serve as the basis for the BSC. This condition then requires a substantial research effort focusing on estimating loss of life and defining economic damages from catastrophic failure floods and deriving appropriate decision rules for a very uncertain and highly sensitive evaluation issue.

## 4. RISK ANALYSIS RESEARCH PROGRAM

The Corps' research program was initiated in conjunction with the NRC study. To a large extent the research program was dependent on the outcome of the NRC study and the Corps' policy formulation in order to focus the research funds and make most efficient use of the limited time allotted to the study. Simultaneously, however, the research activities included assistance in developing the scope of studies for the NRC effort as well as that of the Corps policy, while designing the research effort to be compatible with the anticipated recommendations of the NRC study.

The NRC Committee recommendations and suggestions as well as the Corps' derivative policy guidance seem rather straightforward, if not entirely acceptable, since it represents a distinct departure from a traditional engineering reliability viewpoint. The intent of the careful separation of hazard categories and definition of decision rules, however, was to avoid factoring the many uncertainties of important decision variables inherent in a complete risk analysis because of the numerous unresolved methodological issues enumerated by the NRC Committee. Even though the Corps' Phase I risk analysis is based on a relative or comparative hazard assessment (incremental damages between the "failure" and the "non-failure" flood), there are still many analytical and measurement problems that need to be resolved. These will become apparent upon applying the interim procedures developed in Part III of this report.

The NRC Committee approached the issue of the present applicability of risk analysis to dam safety rehabilitation in the following manner:

> "...the risk analysis approach has provided a significant trend toward improved assessments and toward selecting more rational, site-specific spillway evaluation standards within the last few years. Though risk-cost analyses may appear to represent the most desirable approach to the goal of dam safety (i.e., in quantifying hazard, failure probability, and acceptable damage) at this time, this method has certain important problem areas or limitations that the user needs to consider." (pg. 57)

Among the limitations listed were those delineated by an earlier ICODS (Interagency Committee on Dam Safety, 1983) critique of risk analyses along with other deficiencies listed by the NRC Committee. The following points are listed:

- risk cost analyses requires estimates of the exceedance probability of extreme hydrologic events. These probabilities are highly variable and are likely to affect the choice of alternatives.
- many intangible factors cannot be measured in economic terms (loss of life, social dislocation, environmental effects).
- relevance of analyzing a one-time low probability catastrophic event by annualizing damages (expected value approach) is questionable.
- reliability of hydrologic-hydraulic models has not been sufficiently determined, placing into question many of the critical decision variables needed for economic and loss of life analyses.

These include rate of breach formation, flood stage, travel time, flow velocity and debris load.

- forecasting future development below a dam is highly uncertain.

- reliance on downstream warning and evacuation plans for estimating the threatened population and likely loss of life is questionable.

- depth and duration of overtopping of dams without failure is largely unknown, as are the effects of encroaching on the freeboard and the probability of spillway failure itself.

Nevertheless, despite the many recognized unknowns and uncertainties of applying risk analysis to the dam safety rehabilitation problem, the NRC Committee contends that it is for those very reasons that make risk analysis an attractive technique as long as the following conditions and factors are kept in the proper perspective:

o "Risk-based analyses, as presently performed, generally are not intended to replace appropriately conservative design standards. Rather, risk-based analyses provide additional information to decision makers to help them decide how limited funds can best be allocated to reduce risks.

o Risk-based analyses are not intended to provide a sole basis for making decisions. They only provide a portion of the information needed.

o By performing sensitivity studies, many of the problems with performing risk-based analysis can be minimized and the results bounded.

o The process of performing a risk-based analysis often uncovers factors or sensitivity relationships that might otherwise not be identified.

o Those factors that cannot be measured in economic terms, such as loss of human life, can be accounted for in separate risk-based analyses and given the appropriate weight." (pg. 59)

Keeping in mind these conditions and the fact that the comparative hazard assessment approach (Phase I) to rehabilitation decisionmaking precludes most of the risk analysis problems discussed, the Corps' risk research program is concentrating on developing specific measurement and analysis approaches for

Phase I analysis. Some of the more advanced, probabilistic approaches for risk-cost analysis (Phase II) will also be examined, developed and tested as the results of case studies are evaluated.

## 5. INTERIM PHASE I AND PHASE II ANALYSIS

The interim procedures for Phase I analysis, i.e. categorizing and separating those dams for which the BSC justifies the use of the PMF design criterion from the dam which require more detailed risk analysis are presented in Part III of this report. Establishing the BSC, then, is the fundamental component of Phase I analysis, and a necessary prerequisite to Phase II analysis, if necessary.

The interim procedures for Phase I are laid out in a step-wise manner, providing numerous examples of ways to display the information which is developed as part of the evaluation of the BSC. The organization and display of data is a vital component of this comparative hazard assessment phase, enabling a comprehensive overview of the key considerations and decision variables.

Some of the thorny risk analysis related issues such as estimating the probable loss-of-life (rather than the more easily measureable population at risk) and the expected annual damages, which require an accepted probability distribution for the PMF, will be dealt with in a more rigorous manner as part of Phase II analysis. In the meantime, loss of life is to be estimated based on a simple set of measurement principles and engineering judgement as set forth in the example Phase I Procedures (Part III). However, much of Phase II analysis is dependent of the expected outcome of the research program and the case studies. Thus, while specific, detailed procedures can not be presently offered for FOA analysis, the research program will be focussing first on the probabilistically based analytical framework developed by the Bureau of Reclamation for dam rehabilitation studies. This framework haas been presented in the National Research Councils' report on dam safety criteria (NRC; 1985).

Phase II risk analysis is likely to be a multiobjective decision problem. That is to say that the justification for increasing the level of dam safety beyond the BSC toward the PMF as the design criterion will be based on a more subjective weighting and trading off of several different factors. The risk-cost analysis or tradeoffs are likely to take into account a number of intangible and subjective engineering reliability and social factors. These may include unique locational and population concentration factors; difficulty in evacuating the population given a short warning time; projection of future downstream growth and development factors; unique national interest, etc.

The justification for increments for additional safety beyond the BSC will require that additional risk reduction will have to be explicitly balanced or traded off against increased costs (risk-cost analysis). These issues will be dealt with in greater detail in Part II of this report, which is also largely dependent on the outcome of the research program.

# APPENDIX B

## DAEN-CW/DAEN-EC Letter on Policy for Remedial Dam Modification Measures

DEPARTMENT OF THE ARMY
U.S. Army Corps of Engineers
WASHINGTON, D.C. 20314-1000

REPLY TO
ATTENTION OF

DAEN-CW/DAEN-EC 8 April 1985

SUBJECT: Policy for Evaluating Modifications of Existing Dams Related to Hydrologic Deficiencies

SEE DISTRIBUTION

1. The following policy will be used to make future decisions on the merits of dam safety modifications related to hydrologic deficiencies in lieu of the current policy guidance contained in ER 1130-2-417. Planning for dam safety modification will consider combinations of structural design modifications and nonstructural measures, including downstream actions and changes in water control rules. The recommended plan should be for the dam safety modification which meets or exceeds a base safety standard. The base safety standard will be met when a dam failure related to hydrologic capacity will result in no significant increase in downstream hazard (loss of life and economic damages) over the hazard which would have existed if the dam had not failed. Recommendations for modifications that would accommodate floods larger than the flood identified by the base safety standard must be supported by an analysis that presents the incremental costs and benefits of the enhanced design in a manner that demonstrates the merits of the recommendation.

2. Determination of the flood that identifies the base safety standard (base condition) will require definition of the relationship between flood flows and adverse impacts (loss of life and economic damages) with and without dam failure for a range of floods from the flood that fully utilizes the existing structure up to the probable maximum flood (PMF). Appropriate freeboard necessary to accommodate potential wind and wave conditions will be included for all flood evaluations. Selection of a base condition predicated on the hazard to life from dam failure will require supporting information to demonstrate that the population would actually be threatened. The evaluation should distinguish between population downstream of a dam and the population that would likely be in a life threatening situation given the extent of prefailure flooding, warning time available, evacuation opportunities and other factors that might affect the occupancy of the incrementally inundated area at the time the failure occurs.

3. Examples of the analysis required to develop the base condition are illustrated at Enclosures 1 and 2 for the two basic situations that may be encountered. In the case at Enclosure 1 the difference in hazard with versus without failure may be great enough to recommend the PMF as the base condition. In the case at Enclosure 2 the base condition may be established at a flood less than the PMF. Making recommendations for project modifications exceeding the base condition is covered in paragraph 6.

4. Consideration is being given to formulating decision criteria to assist in deciding the significance of the hazard with versus without failure. At this time it is not clear that such criteria can be established for uniform application to all cases or that such criteria would be appropriate. As a result reporting officers must provide a clear rationale for the selection of the base condition. Careful development and explanation of the supporting material should be provided to permit others in the decision chain to reach independent conclusions.

5. Selection of a base condition also should reflect our traditional concern for economy. Modification costs in the vicinity of the scale of improvement identified as the base condition should be examined for sudden increases in the cost/scale of improvement relationship. This type change could occur for instance when a costly highway relocation is encountered near the scale of improvement identified as the base condition. An adjustment in the base condition may be warranted in some cases. On the other hand, the large increase in costs may be justified if a significant reduction in the hazard with versus without dam failure is achieved.

6. Measures to accommodate floods larger than the base condition may be warranted in some cases. When the value of the project services that would be lost added to repair costs for failure are large enough, costs for structural modifications to prevent failure may be economically justified in spite of the low probability of the floods involved.

7. Conduct of the analysis will require careful application of professional judgment for determining those parameters where data and modeling capability are limited. Therefore, the importance of documenting the logic of the assumptions that are critical to the conclusions and recommendations drawn from the analysis cannot be overemphasized. Also, the evaluation will produce a significant amount of information that can be used throughout the decision-making process, particularly in those cases where it is appropriate to proceed beyond the base condition. The information should be displayed in a format that assists the decisionmaker when evaluating the important tradeoffs involved.

8. We are initiating a study effort that will improve the techniques and procedures needed to implement this policy. The products will be provided to you on a continuing basis. The first step in this process is a workshop on hydrologically deficient dams to be held within 60 days. A representative from each field division will be invited to participate in the workshop and overall study effort. This participation will be used as a means of immediate and continuing transfer of information on techniques and procedures to assist you in implementation of this dam safety policy. Information regarding the workshop is being communicated to each division.

DAEN-CW/DAEN-EC 8 April 1985
SUBJECT: Policy for Evaluating Modifications of Existing Dams Related to Hydrologic Deficiencies

9. A final test of the merits of a proposed modification is the comparison of the total average annual benefits with the annualized modification costs. In the event that the benefits do not exceed the costs, consideration will be given to breaching the dam. The rationale for not selecting the breaching option will be provided if improvement is recommended.

10. These policies will be incorporated into ER 1130-2-417, 30 November 1980, subject: Major Rehabilitation Program and Dam Safety Assurance Program.

FOR THE COMMANDER:

Enclosures

LLOYD A. DUSCHA
Deputy Director
Directorate of Engineering
and Construction

JOHN F. WALL
Major General, USA
Director of Civil Works

DISTRIBUTION:
(see page 4)

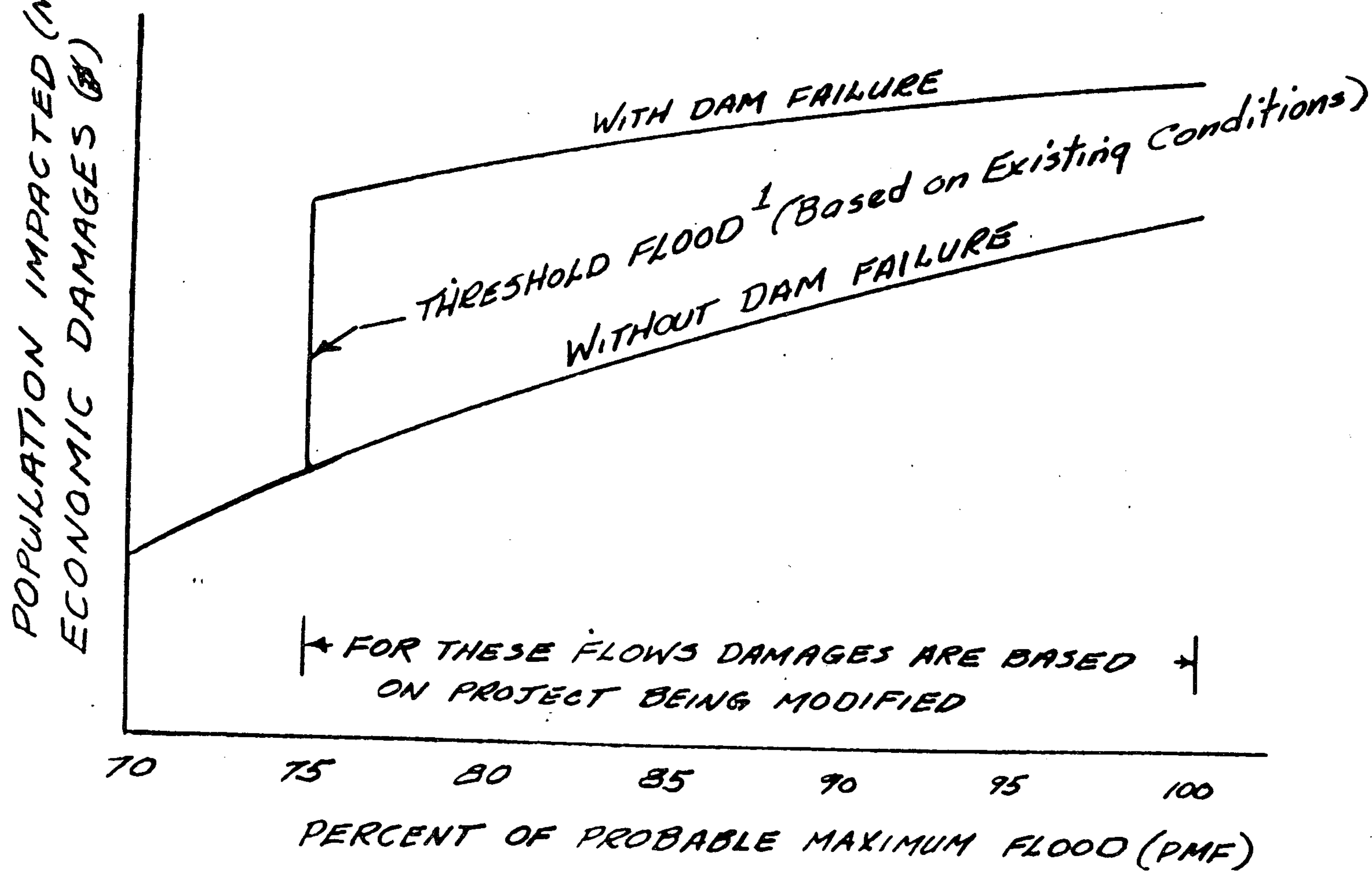
DAEN-CW/DAEN-EC 8 April 1985
SUBJECT: Policy for Evaluating Modifications of Existing Dams Related to Hydrologic Deficiencies

DISTRIBUTION:

CDR USACED, Lower Mississippi Valley
CDR USACED, Missouri River
CDR USACED, New England
CDR USACED, North Atlantic
CDR USACED, North Central
CDR USACED, North Pacific
CDR USACED, Ohio River
CDR USACED, Pacific Ocean
CDR USACED, South Atlantic
CDR USACED, South Pacific
CDR USACED, Southwestern
CDR USACED, Memphis
CDR USACED, New Orleans
CDR USACED, St. Louis
CDR USACED, Vicksburg
CDR USACED, Kansas City
CDR USACED, Omaha
CDR USACED, Baltimore
CDR USACED, New York
CDR USACED, Norfolk
CDR USACED, Philadelphia
CDR USACED, Buffalo
CDR USACED, Chicago
CDR USACED, Detroit
CDR USACED, Rock Island
CDR USACED, St. Paul
CDR USACED, Alaska
CDR USACED, Portland
CDR USACED, Seattle
CDR USACED, Walla Walla
CDR USACED, Huntington
CDR USACED, Louisville
CDR USACED, Nashville
CDR USACED, Pittsburgh
CDR USACED, Charleston
CDR USACED, Jacksonville
CDR USACED, Mobile
CDR USACED, Savannah
CDR USACED, Wilmington
CDR USACED, Los Angeles
CDR USACED, Sacramento
CDR USACED, San Francisco
CDR USACED, Albuquerque
CDR USACED, Fort Worth
CDR USACED, Galveston
CDR USACED, Little Rock
CDR USACED, Tulsa

# DAM SAFETY

## DAMAGE AND POPULATION IMPACTS

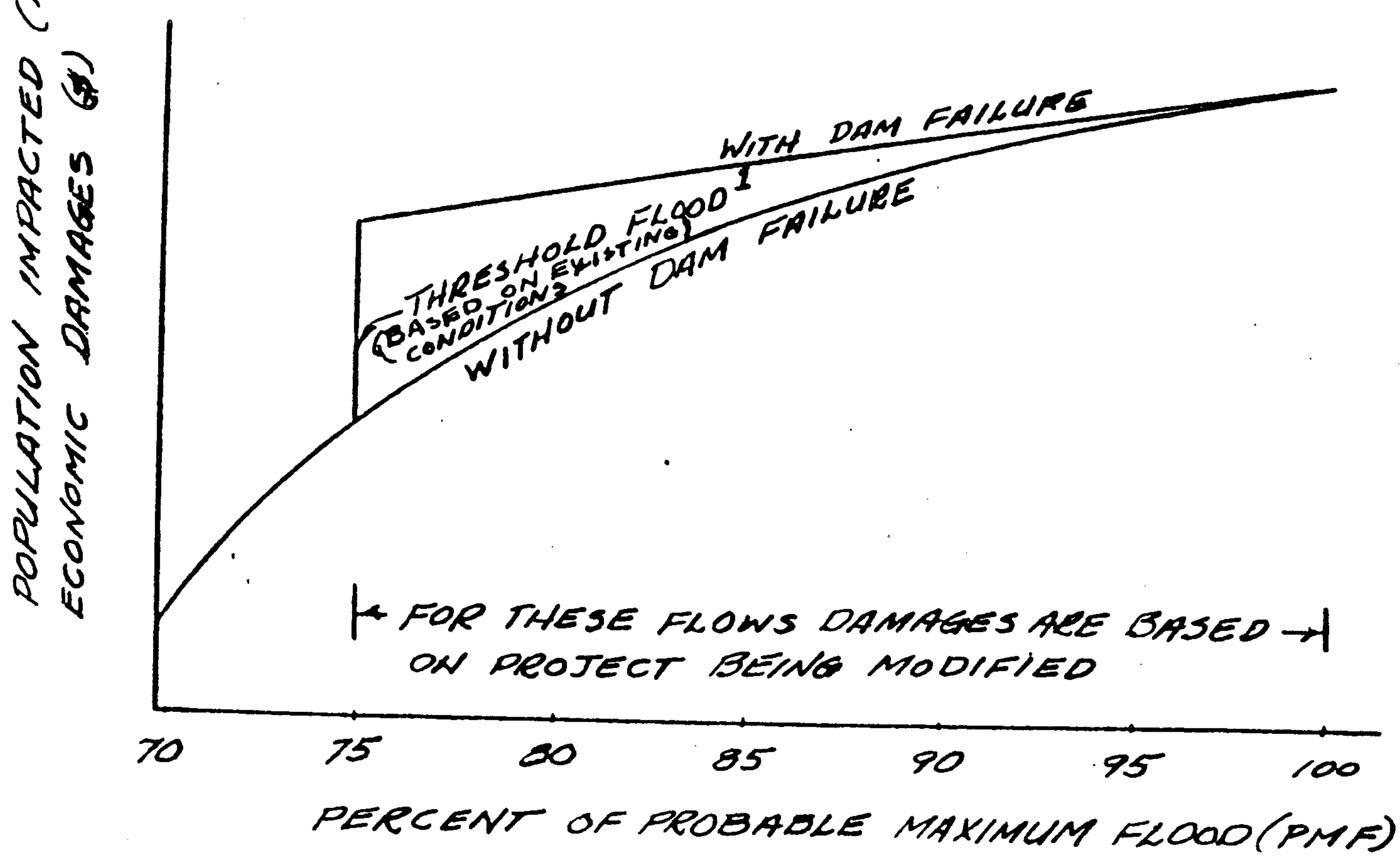



NOTES:
1. PERCENT OF PMF PROJECT CAN PASS WITH APPROPRIATE FREEBOARD
2. THIS CONDITION MAY SUPPORT PROJECT MODIFICATION TO PASS PMF.

ENCLOSURE 1

# DAM SAFETY

## DAMAGE AND POPULATION IMPACTS




NOTES:
1. PERCENT OF PMF PROJECT CAN PASS WITH APPROPRIATE FREEBOARD.
2. THIS CONDITION MAY SUPPORT PROJECT MODIFICATION TO PASS LESS THAN PMF.

ENCLOSURE 2

# APPENDIX C

# APPENDIX D

## Glossary

# APPENDIX E

## References and Bibliography